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JUNE 1971

# THERMIONIC SPACECRAFT DESIGN STUDY
# 120 kw NUCLEAR ELECTRIC PROPULSION SYSTEM

## FINAL REPORT

## VOLUME II – EXTERNAL FUEL REACTOR SPACECRAFT DESIGN

June 30, 1971



Prepared Under Contract JPL 952381
for
Thermionic Reactor Systems Project



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Jet Propulsion Laboratory
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Nuclear Systems Programs
Space Systems
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100p.

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JPL TECHNICAL MANAGER - C. D. SAWYER

THIS WORK WAS PERFORMED FOR THE JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, AS SPONSORED BY THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION UNDER CONTRACT NAS7-100.

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ABSTRACT

Electrically propelled spacecraft designs for a Comet Halley Rendezvous mission, using thermionic reactors as the electrical power source were investigated. Four spacecraft designs were prepared. The four spacecraft designs include two external-fuel reactor concepts (heat pipe cooled diode and independently pumped diode) providing 120 kWe at 40 VDC to the thrust subsystem and two internal-fuel reactor concepts (10 VDC and 40 VDC) providing 120 kWe to the thrust subsystem. The impact of integration with the Space Shuttle, the use of U-233 fueled reactors, alternate EM pumps and main radiator systems is assessed for each of the four spacecraft designs.

The three 40 VDC spacecraft designs are nearly the same size (1.14 m diameter by 20 m to 22 m long) with specific weights from 26 to 30 kg/kWe. The 10 VDC spacecraft design is 27 m long, with a specific weight of about 33 kg/kWe. Integration into the Space Shuttle adds 2 kg/kWe to the 40 VDC spacecraft designs, and 6 kg/kWe to the 10 VDC spacecraft. The use of U-233 fueled reactors reduces the specific weight by 5 kg/kWe for a spacecraft design except the 10 VDC internal-fuel concept.

VOLUME II - EXTERNAL FUEL REACTOR
SPACECRAFT DESIGN

THIS REPORT IS PRESENTED IN THREE VOLUMES:

VOLUME I - SUMMARY

VOLUME II - EXTERNAL FUEL REACTOR SPACECRAFT DESIGN

VOLUME III - INTERNAL FUEL REACTOR SPACECRAFT DESIGN

## EXTERNAL FUEL REACTOR SPACECRAFT DESIGN

This section provides the design definition of the external fuel reactor spacecraft as summarized in Vol. I, Section 4. The external fuel reactor characteristics, on which all the external fuel reactor spacecraft designs are based, are to be presented. The design definitions of the baseline external fuel reactor spacecraft are presented. The first baseline design utilizes a reactor where an independently pumped liquid metal loop cools each diode. The second baseline spacecraft utilizes a reactor whose diodes are independently cooled by means of heat pipes.

Alternate powerplant design studies are presented. These perturbations to the baseline designs, include launch by the ALS to low Earth orbit, the use of DC EM pumps in the primary coolant loop, and replacing the single loop radiator with a radiator of four independent coolant loops, one of which is redundant in rejecting reactor waste heat.

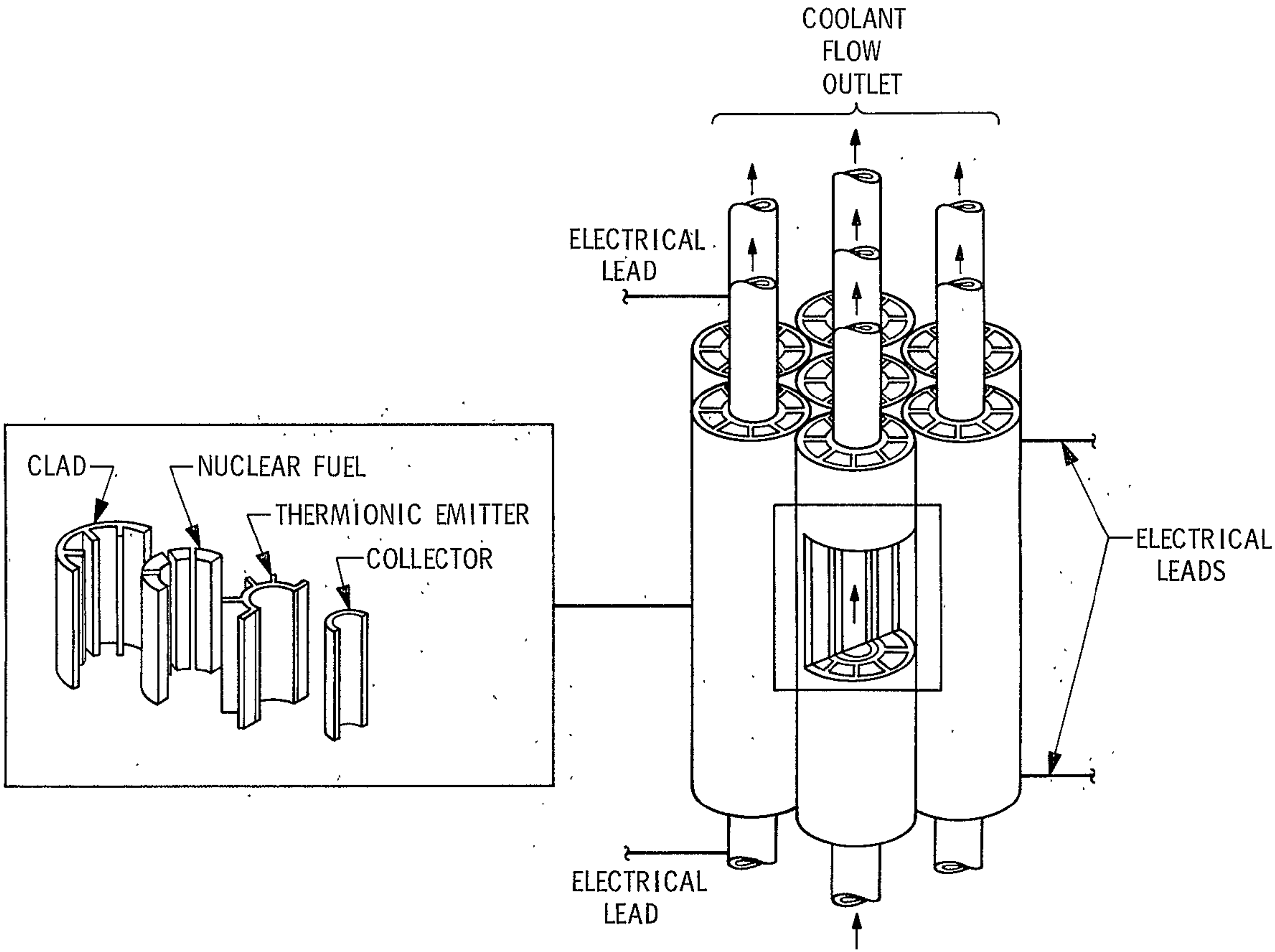
### 1.0 EXTERNAL FUEL REACTOR CHARACTERISTICS

Characteristics of the external fuel reactor as used in this study have been provided by JPL (Reference 1-1). The core-length external fuel element concept is illustrated in Figure 1-1. Each thermionic cell consists of a fuel element which surrounds a cylindrical collector separated from the emitter by a 10 mil gap. Inside the collector is the liquid metal coolant. This configuration is different from the flashlight reactor concept in that the fuel is external to the emitter.

Performance of the external fuel reactor is based on a maximum emitter temperature of $2000^{o}K$, a collector temperature of $1000^{o}K$, and a cesium reservoir temperature of $620^{o}K$. Emitter area of each fuel element is maintained at $111.5 cm^2$. Reactor efficiency is presented in Figure 1-2 and voltage per number of fuel elements in parallel is presented in Figure 1-3. These data are presented as a function of thermal power per TFE, and for collection temperatures of $1000^{o}K$, $1150^{o}K$, and $1300^{o}K$. For this study, diodes of a four-diode group are connected in parallel after which all groups are connected in series to provide a total reactor output voltage of approximately 40 volts.

FIGURE 1-1

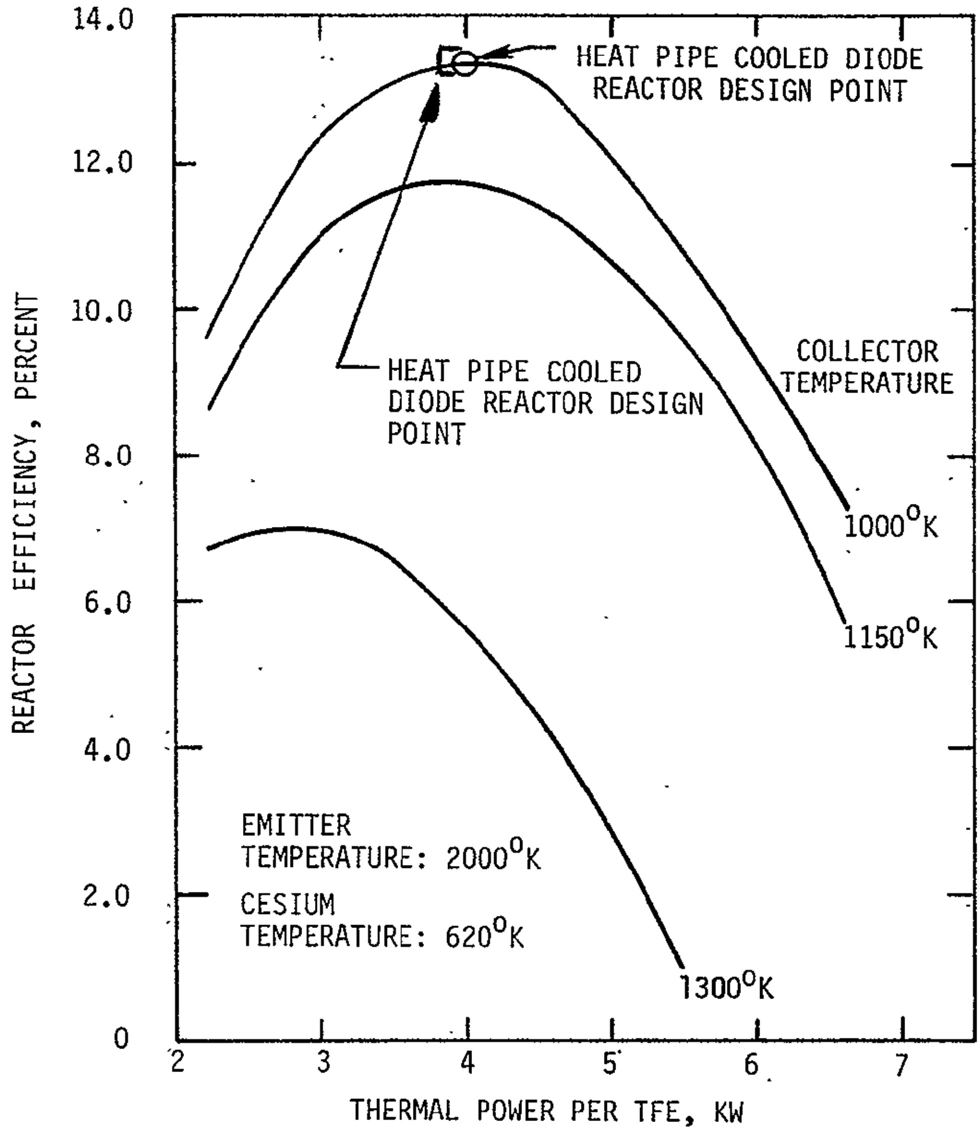
EXTERNAL FUEL THERMIONIC FUEL ELEMENT



# FIGURE 1-2

## EXTERNAL FUEL REACTOR PERFORMANCE

## EFFICIENCY VS. TFE UNIT POWER (JPL DATA)



The independently pumped diode (IPD) reactor and heat pipe cooled diode (HCD) reactor design points are indicated in Figures 1-2 and 1.3, where the IPD reactor consists of 288 TFE's and the HCD reactor consists of 280 TFE's. The IPD design requires eight more TFE units to meet the increased coolant pump work requirements, as discussed in paragraph 2.0 below.

Selection of the optimum number of TFE's within the reactor of each baseline spacecraft design was accomplished with the aid of Figure 1-4, which describes net reactor voltage and reactor waste heat as a function of number of TFE's for a particular reactor electrical output power. For the IPD reactor spacecraft, the design point of 288 TFE's corresponds to reactor output voltage of 38.2 v and reactor waste heat of 1175 kw. This configuration provides the required 135 kWe of reactor electrical output power. Similarly, a 280 TFE configuration of the heat pipe cooled diode reactor provides 130 kWe of electrical power, which corresponds to reactor output voltage of 38.7 v and reactor waste heat of 1110 $kW_t$. The preceding design points were selected such that for each baseline spacecraft, the sum of reactor weight and heat rejection system weight is minimized. Since half of the electrical power is extracted from each end of the reactor and then joined in a common bus, net reactor voltage as indicated in Figure 1-4 for the IPD reactor, and in Figure 1-5 for the HCD reactor, is the product of voltage per TFE's in parallel (Figure 1-3) and the number of parallel diode sets and then diminished by the internal reactor circuit voltage loss given by:

$$\Delta V = I_{TFE} \times N_{TFE} \times (0.855 + 0.124 \times N_p) \times 10^{-5}$$

where:

$\Delta V$ = interconnection voltage loss, v

$I_{TFE}$ = total thermionic fuel element current, amp

$N_{TFE}$ = number of thermionic fuel elements

$N_p$ = number of thermionic fuel elements connected in parallel

Reactor weight and core radius and single TFE diameter are shown in Figure 1-6 as a function of number of TFE's for the baseline U-235 fueled external fuel reactor. The reactor radius is 11.7 cm greater than the indicated core radius.

FIGURE 1-3

EXTERNAL FUEL REACTOR PERFORMANCE
VOLTAGE VS. TFE UNIT POWER (JPL DATA)

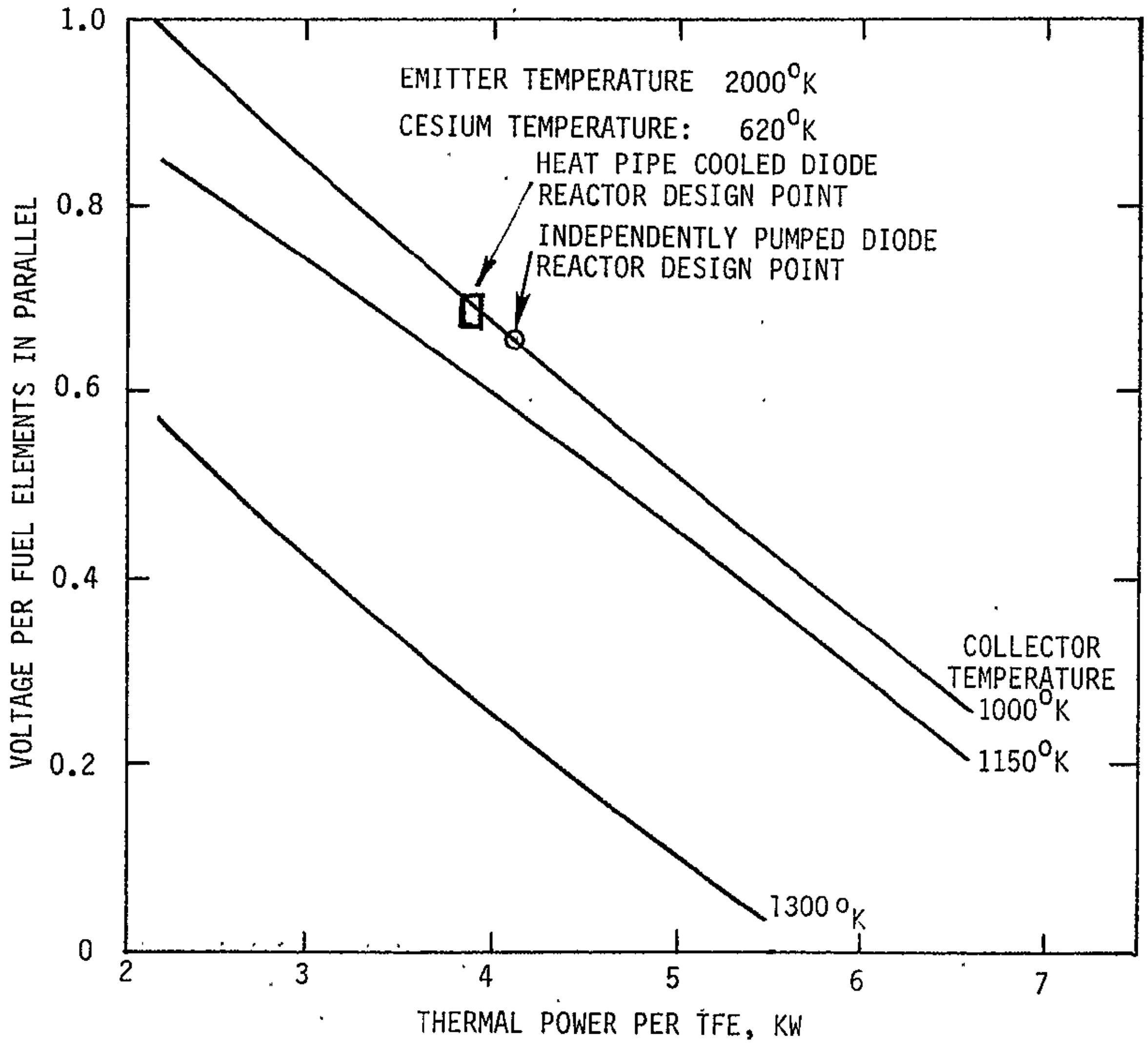
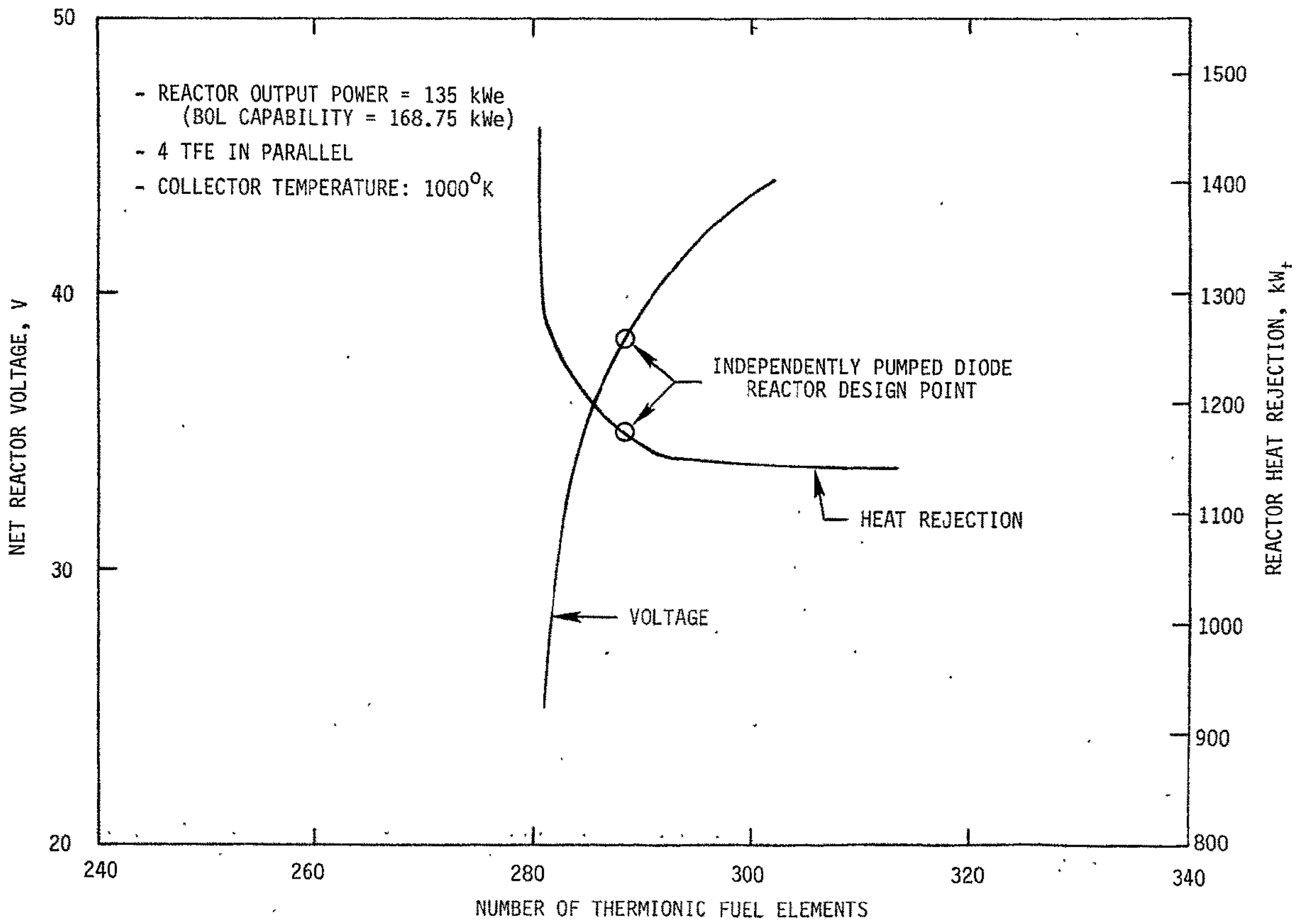


FIGURE 1-4

EXTERNAL FUEL REACTOR PERFORMANCE
INDEPENDENTLY PUMPED DIODE REACTOR



# FIGURE 1-5

## EXTERNAL FUEL REACTOR PERFORMANCE
## HEAT PIPE COOLED DIODE REACTOR

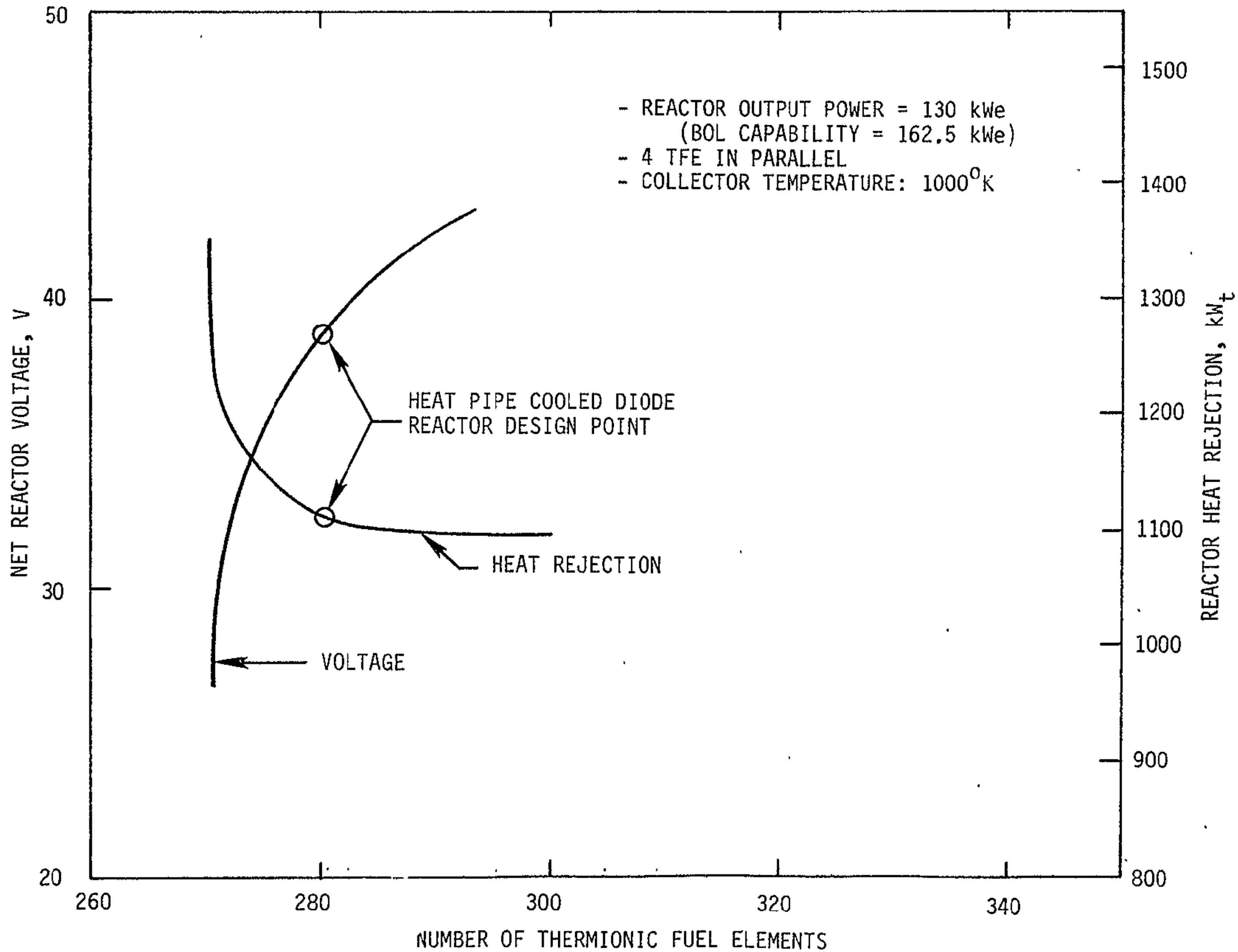
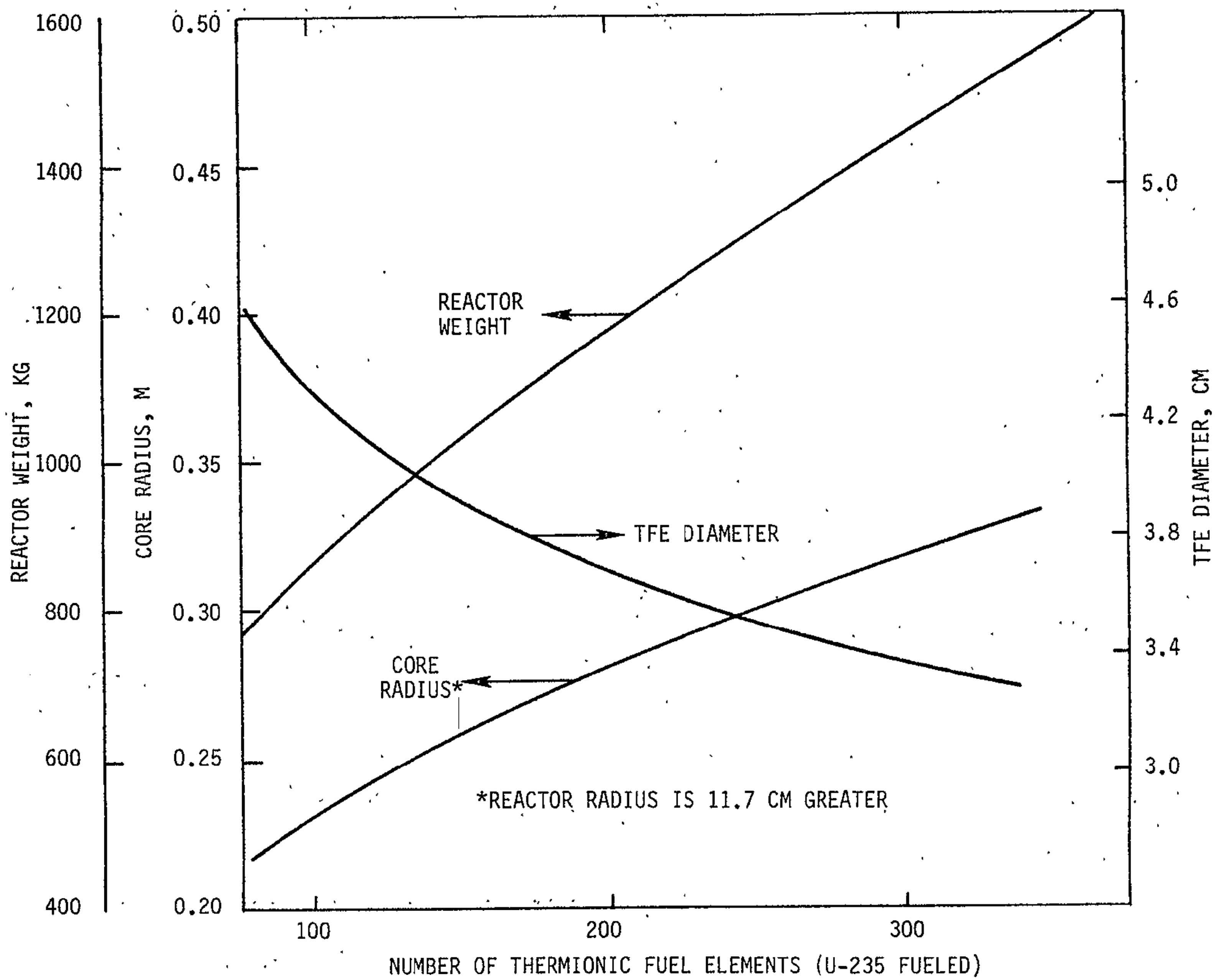


FIGURE 1-6

EXTERNAL FUEL REACTOR CHARACTERISTICS
U-235 FUEL (JPL DATA)



Although the baseline spacecraft designs are based on reactors fueled with U-235, an alternative spacecraft design has been generated for a reactor fueled with U-233. Basically, the external fuel reactor performance characteristics are identical for U-233 and U-235 fueled reactors; however, for the same number of U-233 fueled TFE's reactor weight, core radius, and TFE diameter is given in Figure 1-7.

## 2.0 INDEPENDENTLY PUMPED DIODE REACTOR SPACECRAFT

This section describes the external fuel reactor spacecraft in which each reactor diode has its own independent coolant tube and the coolant is circulated by a multi-ducted DC EM pump. A design layout of the IPD reactor spacecraft is presented in Figure 2-1. A detailed weight breakdown for the baseline IPD reactor spacecraft is presented in Table 2-1. The total spacecraft weight at launch is 8690 kg. The launch vehicle adapter and shroud are jettisoned during launch, shortly prior to injection to Earth escape. The initial spacecraft weight at Earth escape is as follows:

- Propulsion System 3552 kg
- Mercury Propellant 3660 kg
- Low Thrust Propellant Inerts 110 kg
- Net Spacecraft 662 kg

The low thrust propellant weights, which include a ten percent ullage allowance, and the allowable net spacecraft weights were determined from mission analysis for the baseline 940-day Comet Halley rendezvous mission.

The total power delivered to the thrust system is the guideline value of 120 kWe, which is the power level on which propulsion system specific weight, $\alpha$, is based. About 95 percent of the 120 kWe is provided to supply power to the 4000 VDC ion engine screen grid, and about 5 percent supplies power to miscellaneous ion engine loads. After allowances of 5.5 kWe power loss from the low voltage cable, 7.5 kWe required by the DC EM pump and the other power requirements associated with all the 120 kWe spacecraft designs, a total of 135.7 kWe reactor output power is necessary to supply 120 kWe to the thrust system and subsequently, 100 kWe to ion engine beam power. Power balance and distribution for the IPD reactor spacecraft is given in Figure 2-2.

# FIGURE 1-7

## EXTERNAL FUEL REACTOR CHARACTERISTICS
## U-233 FUEL (JPL DATA)
## RADIAL POWER FLATTENED

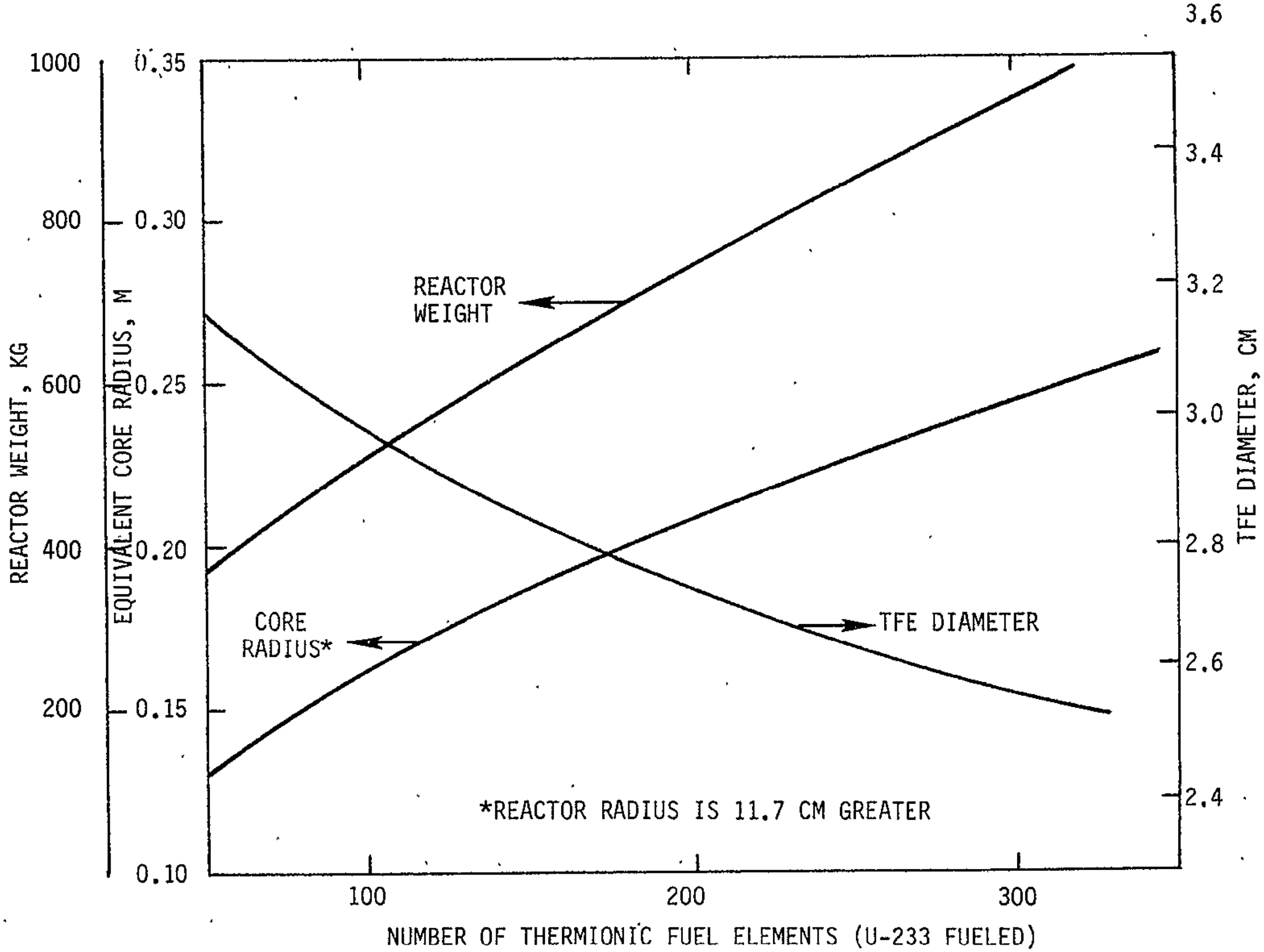


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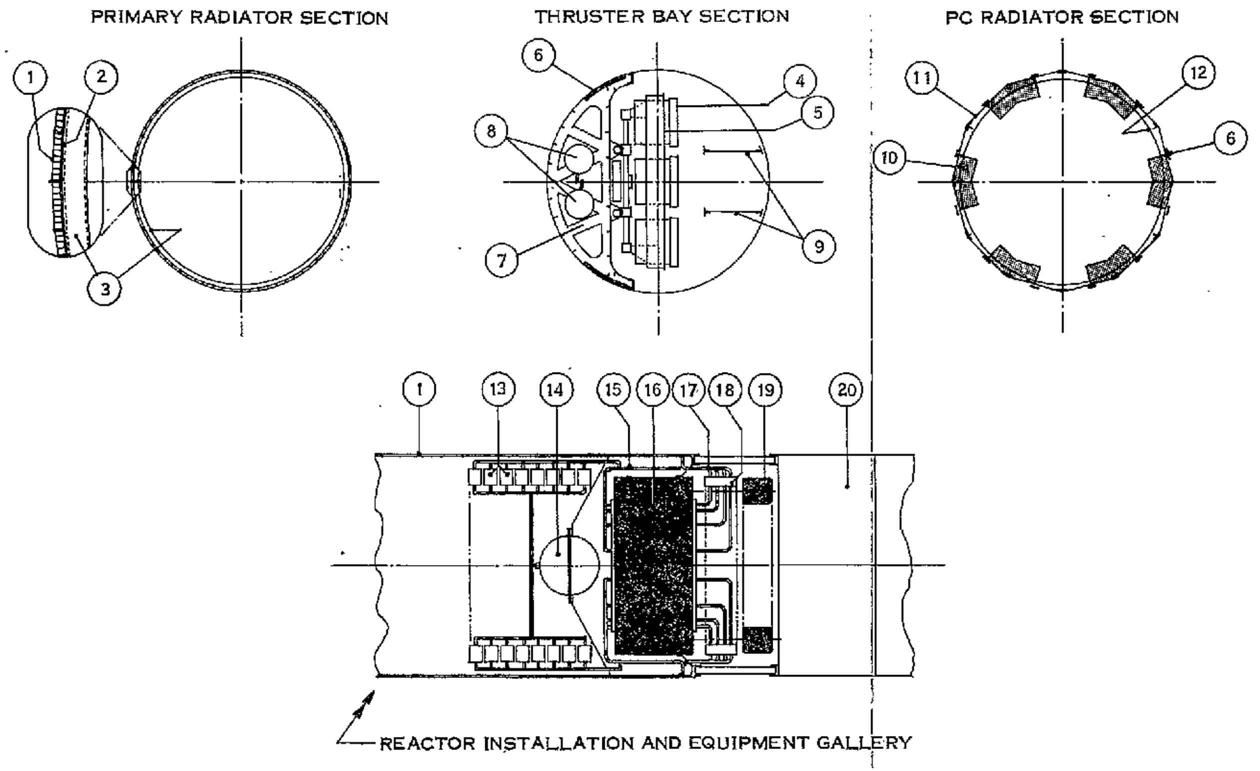
FIGURE 2-1A

# INDEPENDENTLY PUMPED DIODE REACTOR SPACECRAFT DESIGN DETAILS




| ITEM DESCRIPTION |
|---|
| 1. PRIMARY RADIATOR COOLANT DUCTS |
| 2. INSULATOR |
| 3. STIFFENING RING |
| 4. ION THRUSTER |
| 5. ION THRUSTER SUPPORT STRUCTURE |
| 6. LOW VOLTAGE CABLES |
| 7. THRUSTER BAY SUPPORT STRUCTURE |
| 8. EXAMPLE MERCURY FLOW CONTROL SYSTEM |
| 9. LAUNCH SUPPORT STRUCTURE |
| 10. MAIN POWER CONDITIONING MODULE |
| 11. POWER CONDITIONING RADIATOR |
| 12. STIFFENING RING |
| 13. COOLANT DUCT ACCUMULATORS |
| 14. COOLANT PRESSURIZATION TANK |
| 15. REACTOR OUTLET LINES |
| 16. REACTOR (EXTERNAL FUEL) |
| 17. EM PUMP REACTOR INLET LINES |
| 18. EM PUMP ASSEMBLY |
| 19. REACTOR CONTROL ACTUATORS |
| 20. NEUTRON SHIELD |

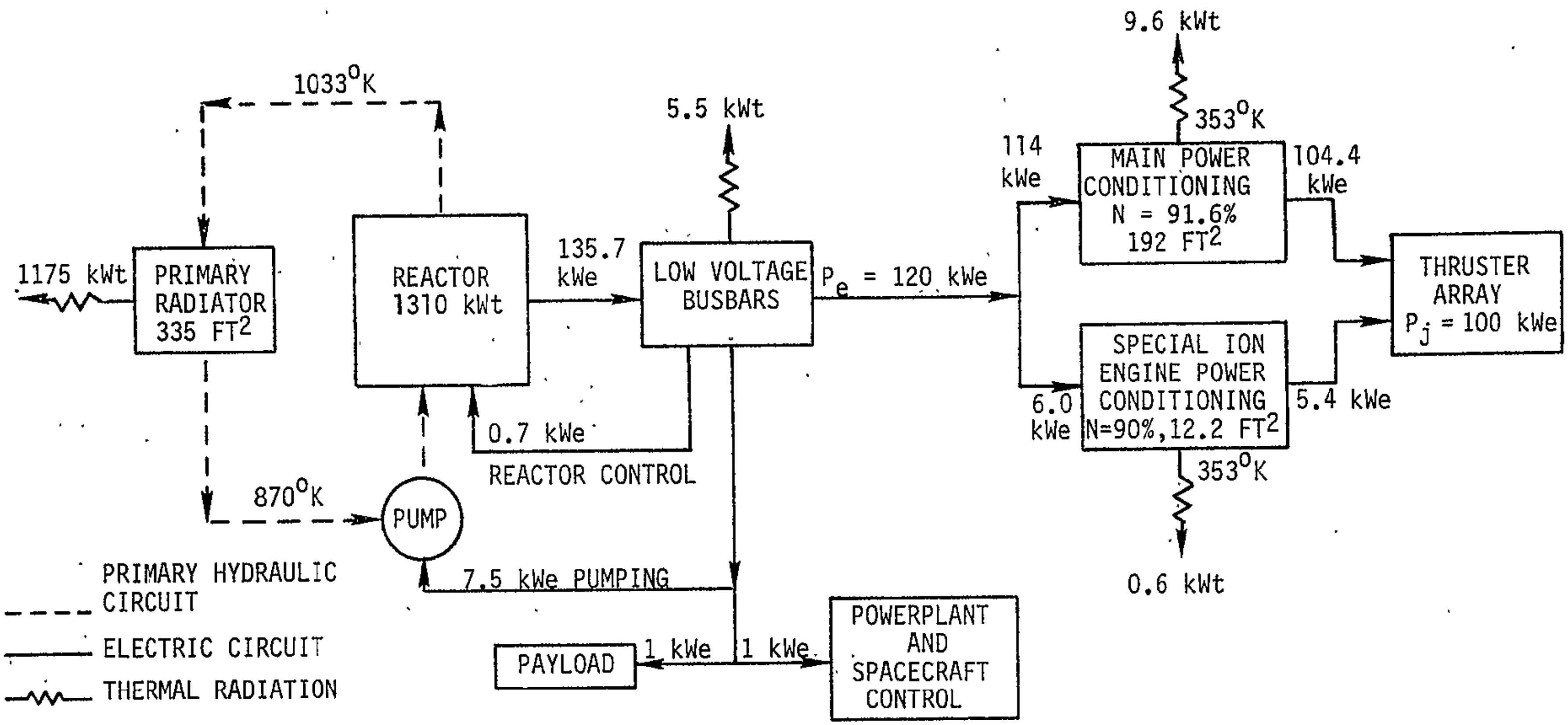
# TABLE 2-1

## WEIGHT SUMMARY
## BASELINE IPD EXTERNAL FUEL SPACECRAFT

| COMPONENTS | WEIGHT, KG | | |
|---|---|---|---|
| PROPULSION SYSTEM | | | 3552 |
| POWER SYSTEM | | 2714 | |
| REACTOR | 1410 | | |
| HEAT REJECTION | 677 | | |
| NEUTRON SHIELD | 519 | | |
| PUMP LOW VOLTAGE CABLE | 48 | | |
| STRUCTURE | 60 | | |
| THRUST SYSTEM | | 838 | |
| THRUST ARRAY | 213 | | |
| POWER CONDITIONING | 306 | | |
| POWER CONDITIONING RADIATOR | 96 | | |
| LOW VOLTAGE CABLE | 140 | | |
| HIGH VOLTAGE CABLE | 3 | | |
| STRUCTURE | 80 | | |
| PROPELLANT SYSTEM | | | 3770 |
| PROPELLANT | | 3660 | |
| TANKS AND DISTRIBUTION | | 110 | |
| NET SPACECRAFT | | | 662 |
| FLIGHT SHROUD WEIGHT PENALTY | | | 706 |
| LAUNCH VEHICLE PAYLOAD REQUIREMENT | | | 8690 |

FIGURE 2-2

EXTERNAL FUEL INDEPENDENTLY PUMPED DIODE SPACECRAFT - 120 kWe
POWER BALANCE AND DISTRIBUTION



Spacecraft subsystem components are discussed in the following sections.

## 2.1 POWER SYSTEM

The power system of the IPD reactor spacecraft is comprised of the reactor, heat rejection, shield, and EM pump low voltage cable subsystems. Total weight of the power system is 2714 kg.

### 2.1.1 Reactor Subsystem

Performance characteristics of the external fuel reactor are presented in Section 1.1. For the baseline IPD reactor spacecraft 135.7 kWe of reactor output electrical power are required in order that 120 kWe are supplied to the thrust system. Selection of the number of TFE's that would provide the required reactor output power for a minimum weight condition has been presented on Figure 1-4. For the IPD reactor spacecraft 288 TFE's supplies 135 kWe (168.8 kWe BOL) at a voltage level of approximately 38.2 V and heat rejection of 1175 $kW_t$. This data corresponds to the external fuel reactor characteristics discussed in Section 1.1 for reactor diode emitter temperature of 2000°K and diode collector temperature of 1000°K. The curves of Figure 1-4 are for a particular power requirement where only the number of TFE's has been varied. Since groups of 4 TFE's are connected in parallel and the groups subsequently connected in series, the total number of TFE's must be a multiple of four.* A decrease in the number of TFE's from the baseline value of 288 to 284 reduces reactor weight, but there is a more significant increase in reactor waste heat generated, hence, required radiator area. Conversely, an increase in the number of TFE's from the baseline value to 292 causes a larger increase in reactor weight while the reactor waste heat rejection rate does not decrease appreciably.

Characteristics of the external fuel reactor used for the IPD spacecraft is presented in Table 2-2. Reactor size and weight have been obtained from the data on Figure 1-6 in Section 1.1. Reactor weight for the IPD reactor spacecraft is 1410 kg, total reactor diameter including core and reflectors is approximately 0.85 m, and the diameter of each TFE is 3.4 cm.

---

*In addition, in establishing a good symmetric reactor design, certain numbers of TFE's are preferrable. For this study, the final adjustment to one of these numbers was not made; however, the influence on the final design will be small.

TABLE 2-2

EXTERNAL FUEL REACTOR CHARACTERISTICS FOR
IPD REACTOR SPACECRAFT

| PARAMETER | VALUE |
|---|---|
| REACTOR OUTPUT POWER CAPABILITY | |
| BOM | 170 kWe |
| EOM | 135 kWe |
| OUTPUT VOLTAGE | 38.2 |
| EFFICIENCY | 13.4 % |
| NUMBER OF TFE'S | 288 |
| DIODE THERMAL POWER | 36.5 $w/cm^2$ |
| DIODE EMITTER TEMPERATURE | $2000^{o}K$ |
| DIODE COLLECTOR TEMPERATURE | $1000^{o}K$ |
| CESIUM RESERVOIR TEMPERATURE | $620^{o}K$ |
| TFE DIAMETER | 3.4 cm |
| CORE RADIUS | 31.5 cm |
| REACTOR RADIUS | 43.2 cm |
| REACTOR WEIGHT | 1410 kg |

## 2.1.2 Shield Subsystem

In accordance with the established guidelines for this study, payload and power conditioning electronics have been shielded to neutron and gamma integrated dose limits of $10^{12}$ nvt (En > 1 Mev) and $10^{7}$ rads, respectively. Data on which both the neutron and gamma shields are based have been obtained from Reference 2, as a result of analyses conducted by Oak Ridge National Laboratory.

### 2.1.2.1 Neutron Shield

The neutron shield consists of a lithium hydride stainless steel honeycomb enclosed in a stainless steel can. The lithium hydride performs most of the required neutron shielding with additional shielding neutron attenuation contributed by the mercury propellant. For the 940-day Comet Halley rendezvous mission, which is characterized by 666 days of low thrust propulsion time, the neutron shield requirements as a function of separation distance between the reactor and radiation-sensitive equipment are presented in Figure 2-3. Since the separation distance for the IPD reactor spacecraft as well as the other 120 kWe spacecraft is 4.9 m, 51 cm of lithium hydride is required. Consequently, the neutron shield subsystem is composed of 393 kg of lithium hydride and 126 kg of stainless steel, about three percent of the lithium hydride by volume.

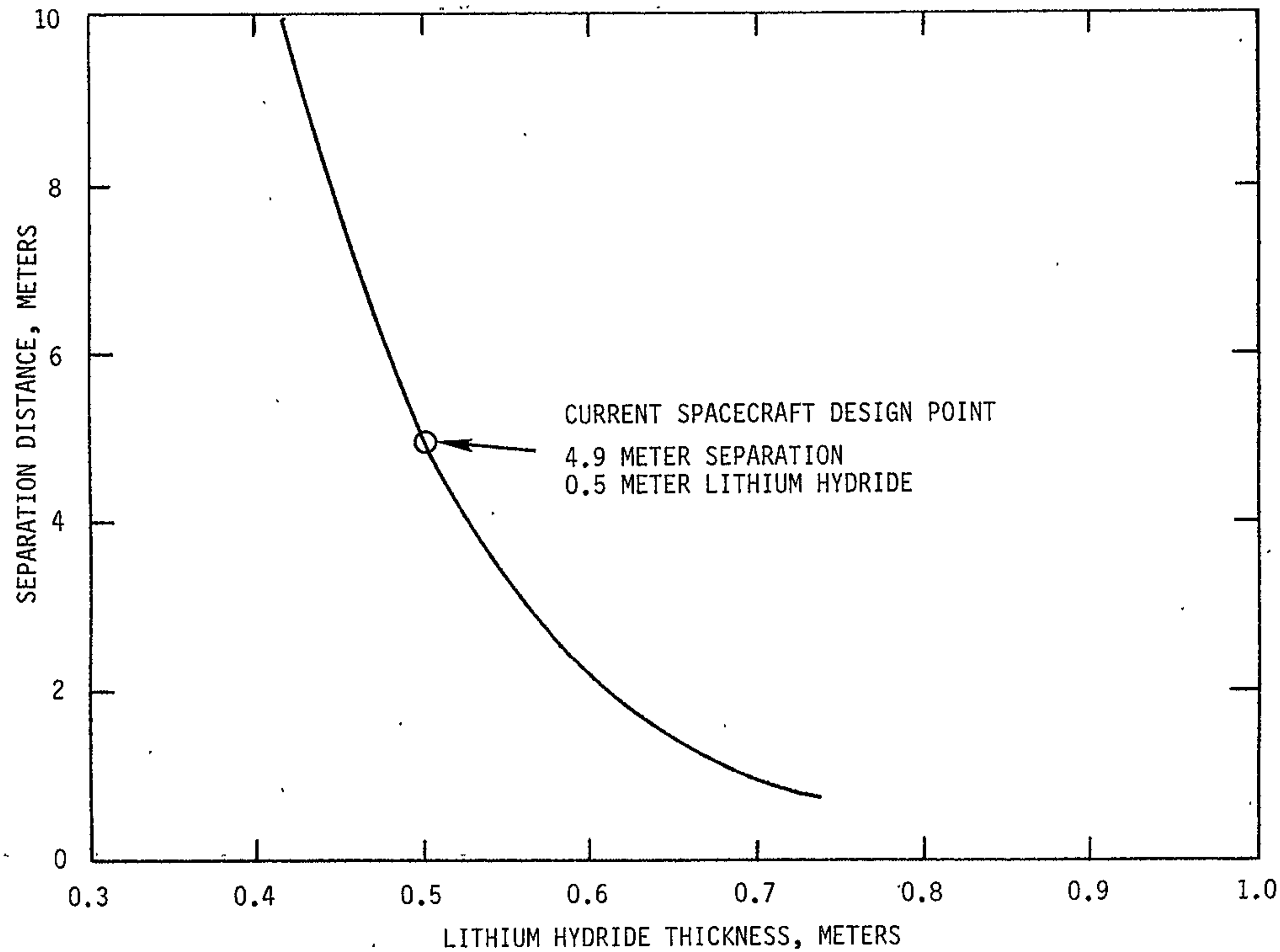
Based on the neutron shield heating relationships employed in Vol. I, Reference 3-4, no auxiliary, active cooling of the shield is required in order to maintain the shield temperature below 812°K. Heat is conducted from the frontal face of the shield by the lithium hydride and stainless steel components to the outer surface of the shield where it is radiated directly to space.

### 2.1.2.2 Gamma Shield

The primary gamma shielding for the IPD reactor spacecraft is provided by the mercury propellant located in two 1.14 m diameter tanks that are positioned on either side of the thruster bay. The cylindrical geometry of 26.4 cm thickness is required to provide the necessary gamma shadow shield, and the dual tanks are required to maintain coincidence of the center-of-gravity with the center-of-thrust throughout the mission for the side thrust spacecraft configuration.

FIGURE 2-3

NEUTRON SHIELD REQUIREMENTS,
940 DAY COMET HALLEY MISSION



For the 940-day Comet Halley rendezvous mission, baseline spacecraft diameter was selected such that initial propellant thickness is adequate to meet the gamma shielding requirements. Therefore, the need for permanent, heavy gamma shielding, such as tungsten or depleted uranium, has been eliminated. Figure 2-4 shows the permanent gamma shielding requirements as a function of spacecraft diameter for the 940-day Comet Halley rendezvous mission. Typical of the weight penalties potentially associated with permanent gamma shielding, it is noted that a spacecraft diameter increase to 1.7 meters would require about one centimeter of tungsten permanent gamma shielding. This would weigh 430 kg and constitute a weight penalty of about 3.6 kg/kWe at the 120 kWe power level.

In order that tungsten permanent gamma shielding is not required for the baseline spacecraft, a spacecraft diameter of 1.14 m was selected. As shown in paragraph 2.1.3, a diameter of 1.14 m allows sufficient space for the IPD reactor and also does not unduly constrict the diameter of the 288 tubes which comprise the main heat rejection subsystem.

### 2.1.3 Heat Rejection Subsystem

The heat rejection subsystem of the IPD reactor spacecraft consists of the primary radiator and the multi-ducted DC EM pump. As indicated in Figure 2-2, the primary heat rejection subsystem is designed to reject 1175 kwt from 288 TFE's. Because the reactor has been designed for 20 percent diode losses, the primary radiator must be capable of operating at the more severe end-of-life thermal conditions.

#### 2.1.3.1 Main Radiator

The basic characteristic of the IPD reactor is that each of the reactor diodes has its own, independent coolant tube, which is located in the center of the reactor diode and extends the entire length of the diode. The coolant tubes emerge from the reactor, travel the length of the radiator, pass through the EM pump, and return to the reactor. The coolant loop scheme for the IPD reactor spacecraft is represented in Figure 2-5, where for clarity only three adjacent sets of four diodes are shown. Through the entire circulatory system each set of four diodes is at a different potential than the other 71 sets because of their

FIGURE 2-4

PERMANENT GAMMA SHIELD REQUIREMENTS, 940-DAY COMET HALLEY MISSION

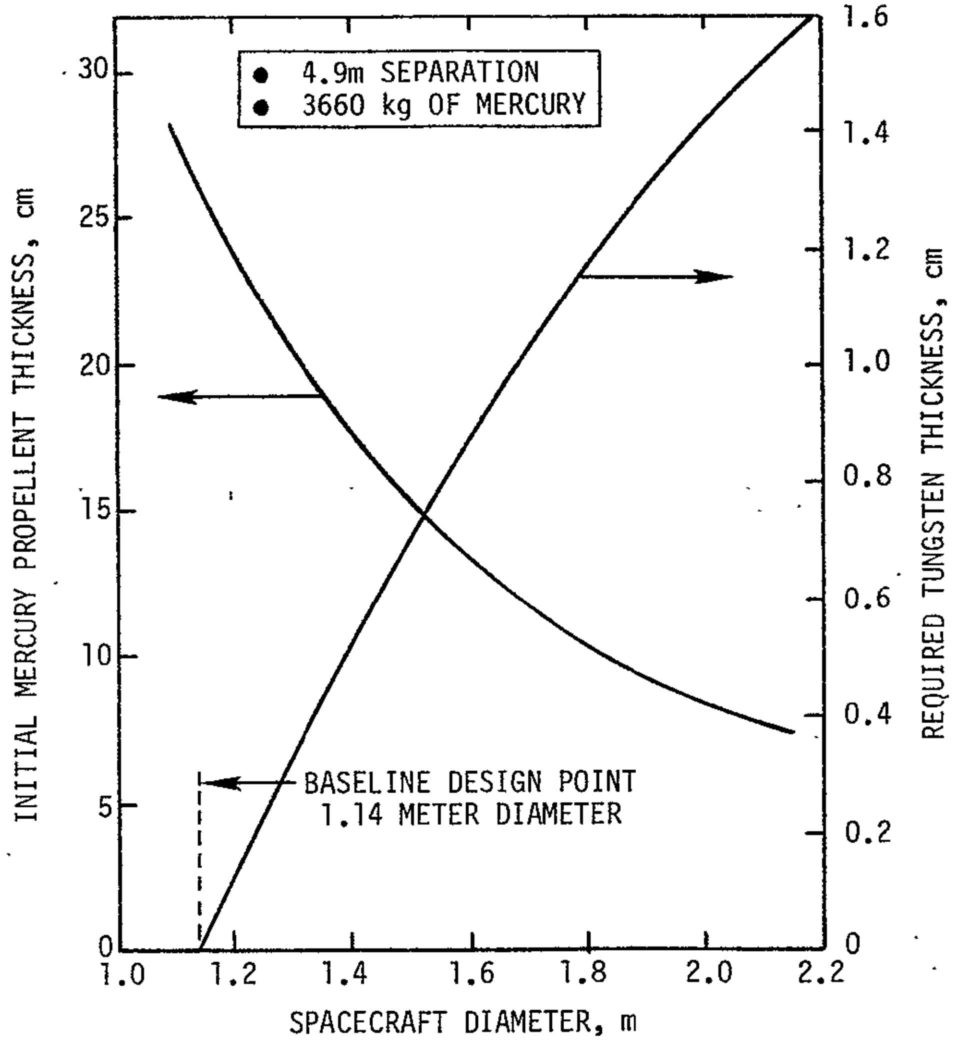
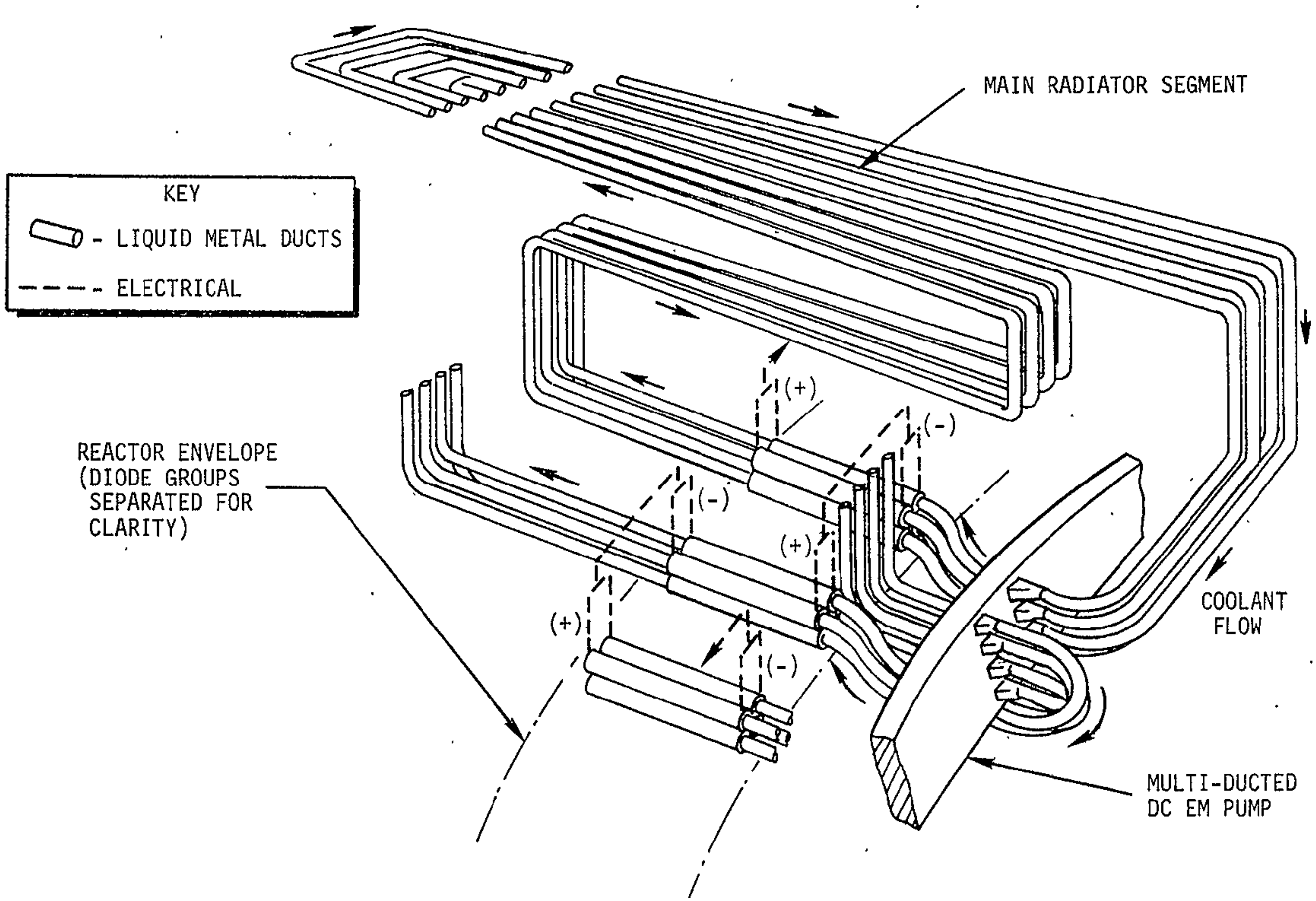


FIGURE 2-5

CANDIDATE PRIMARY HEAT REJECTION
AND ELECTRICAL SYSTEM-INDEPENDENTLY PUMPED DIODE
EXTERNAL FUEL REACTOR SPACECRAFT



series electrical connection and must, therefore, be electrically isolated from the other sets. A technique for accomplishing this is presented in Figure 2-6.

The cylindrical main radiator has 1.14 m diameter and consists of 576 stainless steel tubes. An iterative procedure was employed to determine coolant temperature drop through the main radiator and optimum tube configuration that results in a minimum weight configuration. For radiator inlet temperature of $1033^{\circ}K$, coolant temperature drop of $167^{\circ}K$ is required in order to maintain a reasonable level of coolant pumping power. This resulted in a NaK-78 flow rate of 0.0277 kg/sec. Then, based on these temperature conditions, optimum channel height for a rectangular cross-section of constrained channel width was obtained from the data of Figure 2-7. Channel wall thickness of 0.063 mm corresponds to the required meteoroid protection for 0.95 overall radiator survival probability and for an allowance of 43 tube failures from the total number of 288 tubes. Optimum tube dimensions as indicated in Figure 2-7 are 0.92 mm width by 1.0 mm height. The associated pressure drop through the radiator is approximately $5 \times 10^{4}$ $n/m^{2}$. The pump subsystem weight that was calculated for Figure 2-7 is discussed in the following paragraph.

2.1.3.2 DC EM Pump

The baseline IPD reactor spacecraft employs a multi-ducted DC EM pump to circulate NaK-78 through the coolant loops. The primary requirements on pump design are that each of the coolant loops be pumped independently and each set of 4 loops be electrically insulated from contiguous sets. A parametric design study, Reference 4, has been completed as part of the spacecraft design study and is based on the concept identified by JPL (Reference 3).

The DC conduction pump design that was considered in this study project is arranged so that all diode cooling passages would be individually pumped, and the many pumps arranged with the iron in the form of a torus for best overall compactness.

A DC conduction pump for liquid (alkali) metal operates by having the DC current, which passes through the metal in the duct passage, react with the electro-magnetic field in the adjacent pole pieces like

FIGURE 2-6

CANDIDATE MAIN RADIATOR ELECTRICAL INSULATION STRUCTURE DESIGN

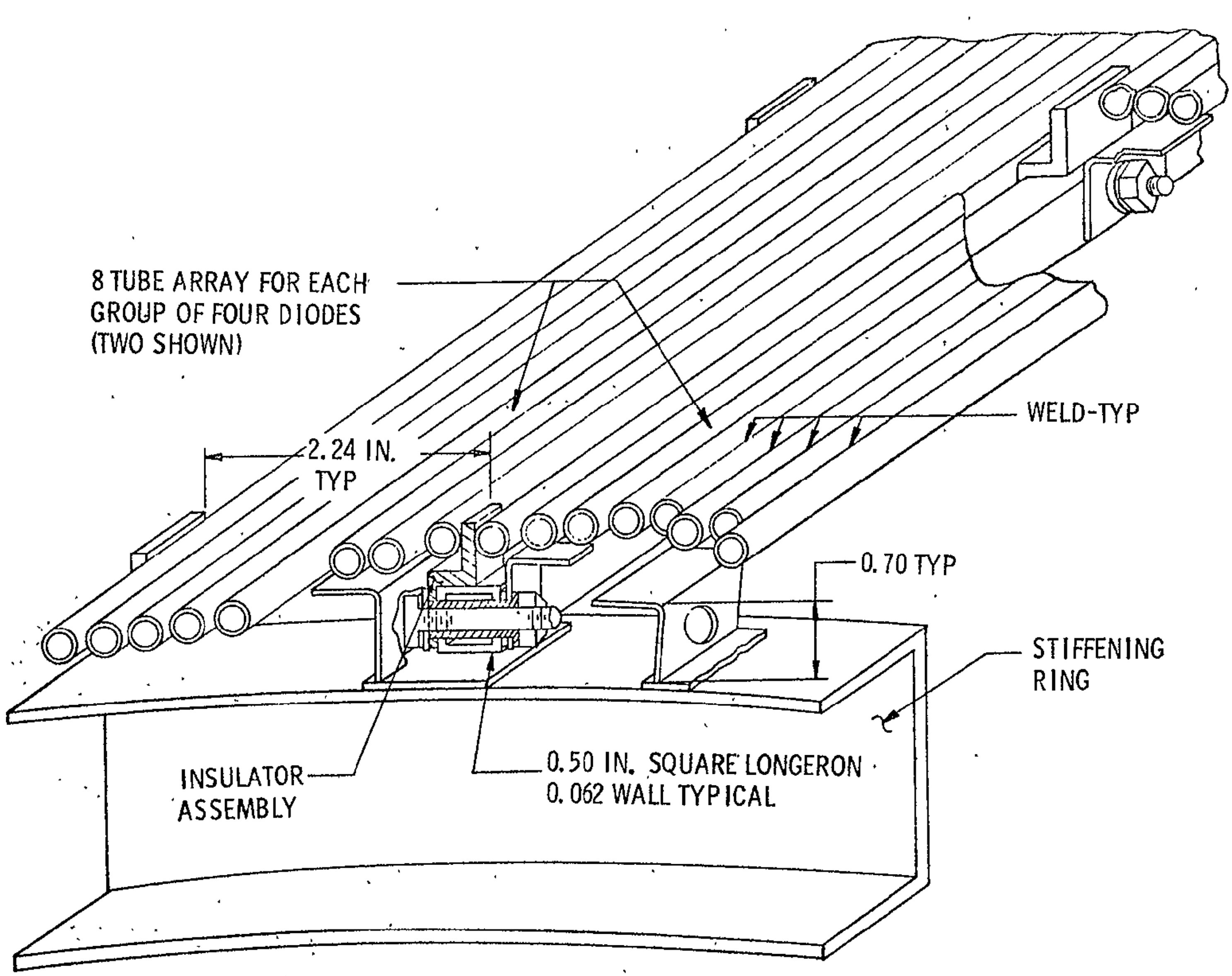
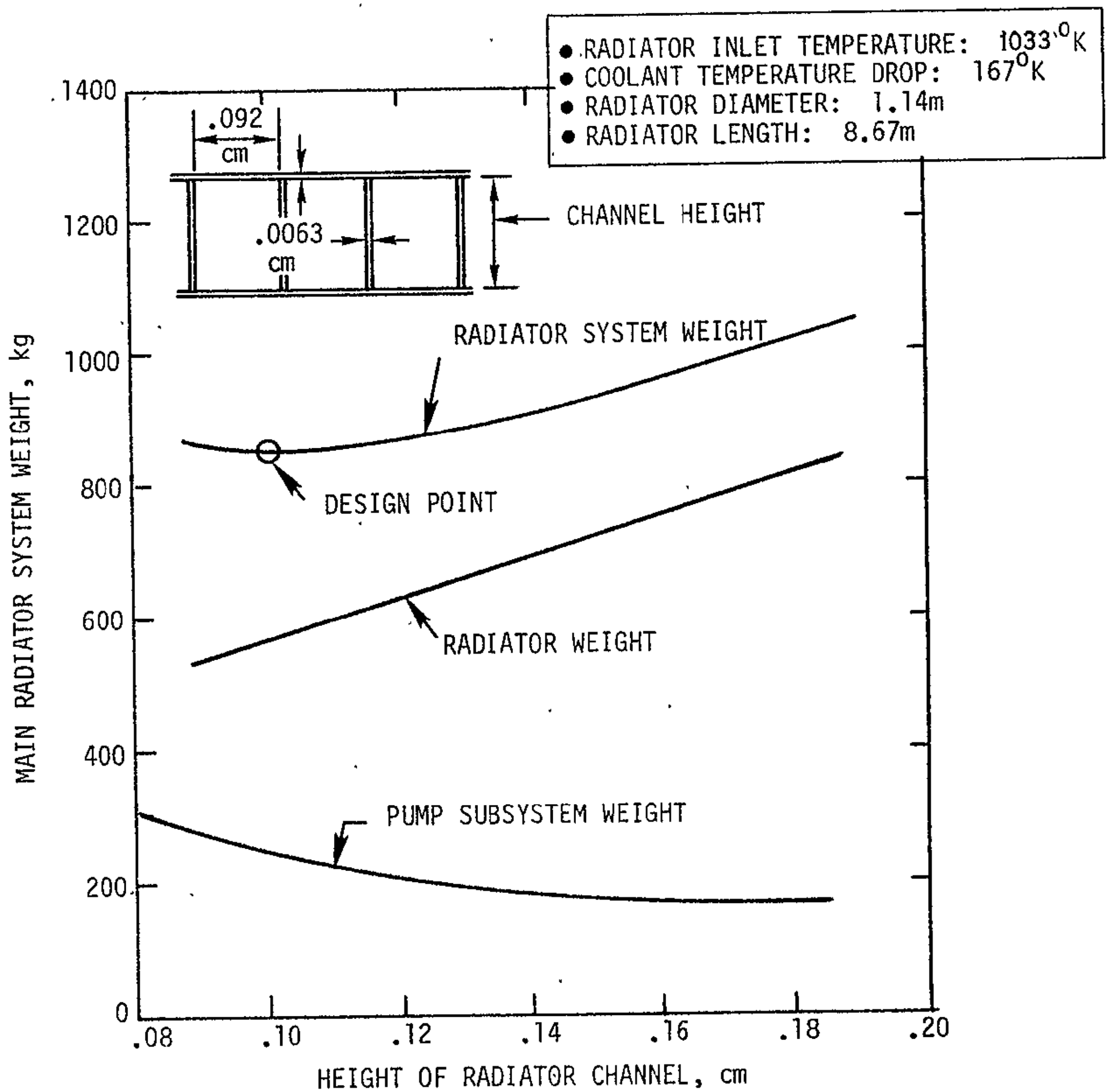


FIGURE 2-7

MAIN RADIATOR CHARACTERISTICS FOR IPD EXTERNAL FUEL REACTOR SPACECRAFT



conductors in the rotor of a DC motor. In the design considered in the study, the field winding is in series with the duct connections so the same current goes through both the windings and the metal in the duct.

An example layout for the pump design selected for the mechanical study is shown in Figure 2-8. Each pump duct includes four channels (to four diodes) and two electrically insulated ducts are included in each gap with liquid metal assumed to flow in opposite directions for flux compensation purposes (See Figure 2-7). Proper arrangement of connecting ducting can be employed to provide flow through the reactor in only one direction. Outside diameter of the pump assembly is 1.14 m; it is 16 cm thick (not counting tube connections), and inside diameter is 84 cm. All coil ends and duct electrical connections are brought to the outside edge of the ring for final interconnection and power lead attachment. The pump ducts are supported from insulated strips joining the outer shell and inner shell. Gaps between the core pieces and ducts permit differential thermal expansion between magnet cores, the ducts and the outer shell. If required, cooling of the cores may be accomplished, as shown, by a coolant duct passing through the cores. For cooling the magnet windings it is proposed to wind the coils on helically grooved alumina pieces which conduct the $I^2R$ coil loss to the cooled iron. Details of the duct selected for the layout, involving four channels, are shown in the enlarged view of the drawing (Figure 2.8).

A series of pump designs was determined by means of an iterative process which provided optimization with respect to the basic variables of channel, fluid velocity, duct dimensions, flux density, and a non-dimensional "slip" parameter, for the above ranges of low, pressure, and number of channels per duct (made up of channels) carrying fluid and current in opposite directions to obtain compensation of the pump current mmf effect upon the magnetic field.

Each duct, consisting of "n" parallel channels, is electrically in series with one magnet coil. For this study each duct is considered to be supplied by a single group of thermionic diodes connected in parallel, providing a potential of 0.7 volts. Of course, the duct groups could all be electrically connected together in series and

supplied by the total output of the diodes. However, this would create operating problems if a channel or related radiator tube were to leak and lose the NaK.

In the pump design calculation, the following assumptions were made:

- Pump Hydraulic Loss: This includes acceleration and diffusion loss plus viscous friction loss in pumping duct. Viscous loss is calculated using Hartmann No. and Reynolds No. Acceleration and diffusion loss were assumed to total .25 of a velocity head (Reference 5).
- Fringing Flux: This is determined by two flux plots in planes at right angles. It is determined that the flux density in the magnet is within saturation limits for the material (Hiperco 27).

Results of the pump design calculations are shown in Figure 2-9 through Figure 2-14 where pump weight, efficiency and current per pump duct are presented as a function of heat rejection subsystem pressure drop, number of channels is parallel, and flow rate. The weight of the pumps includes magnet core, coils, and pump ducts. Structural weight, which adds to the EM weight, varies from 10 percent (8 ducts) to 18 percent (4 ducts) of the total pump weight.

Estimated pump efficiency reaches a maximum of 13 percent with eight channels and flow rate of 65 cc/sec. Estimated pump duct current as shown in Figures 2-13 and 2-14. There is little change with number of channels and low flow rates, but there is a definite effect with the higher flow of 65 cc/sec.

The pump is designed for a potential of 0.7 volts across one duct with four channels. The design also assumes that each duct is connected to a diode group, and not all in series to the total output voltage which is about 40 v. This design requires further study because bringing power to each duct will involve extensive high current wiring, but will permit one or several ducts to cease functioning if liquid metal is lost in any of them without shutting down the entire pump.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

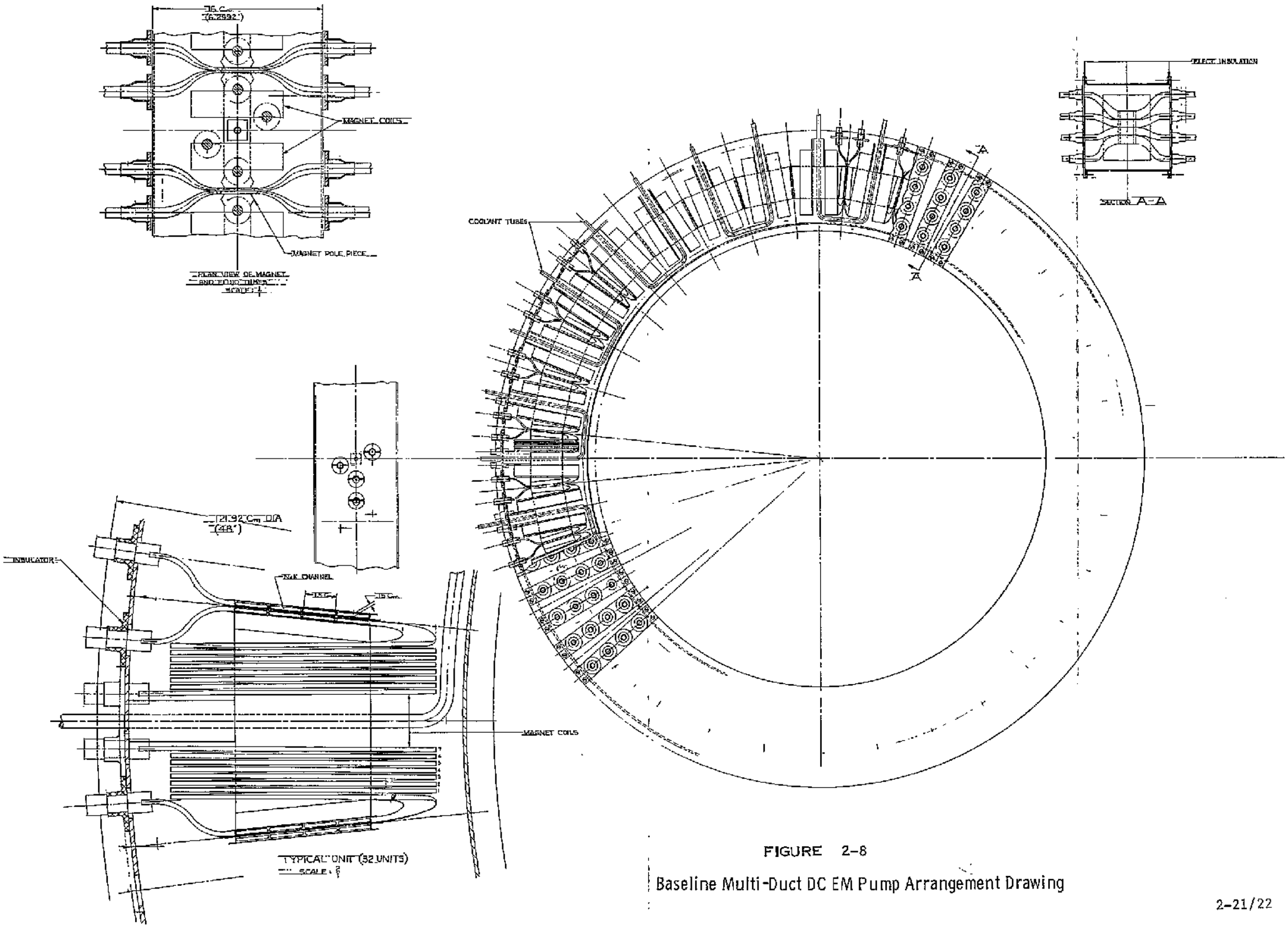



FIGURE 2-8

Baseline Multi-Duct DC EM Pump Arrangement Drawing

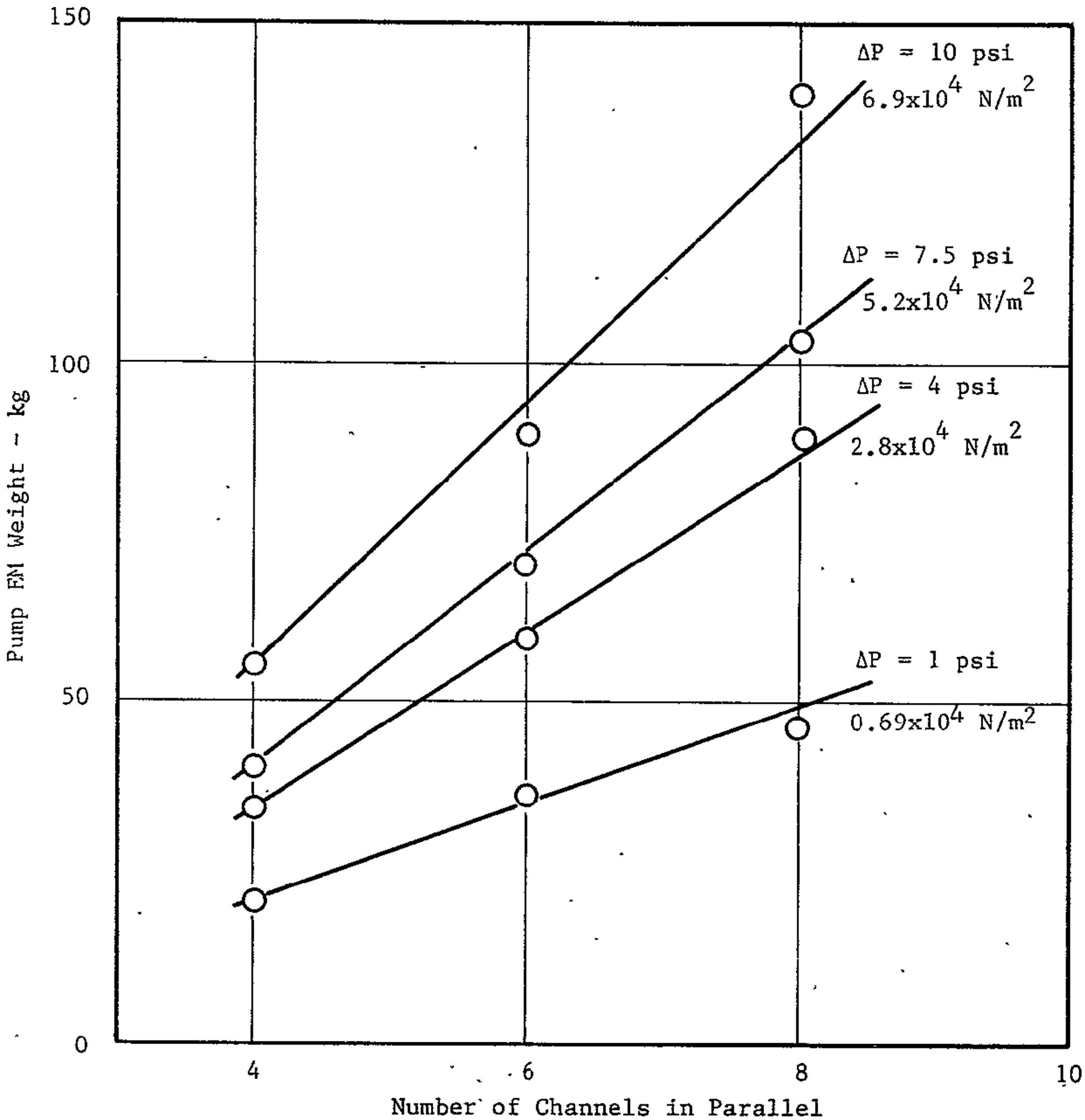



Figure 2-9. Pump Electromagnetic Weight vs Pressure Rise and Number of Channels in Parallel with Flow of 45 cc/sec (0.07 lb/sec) NaK 78 at 1400°F.

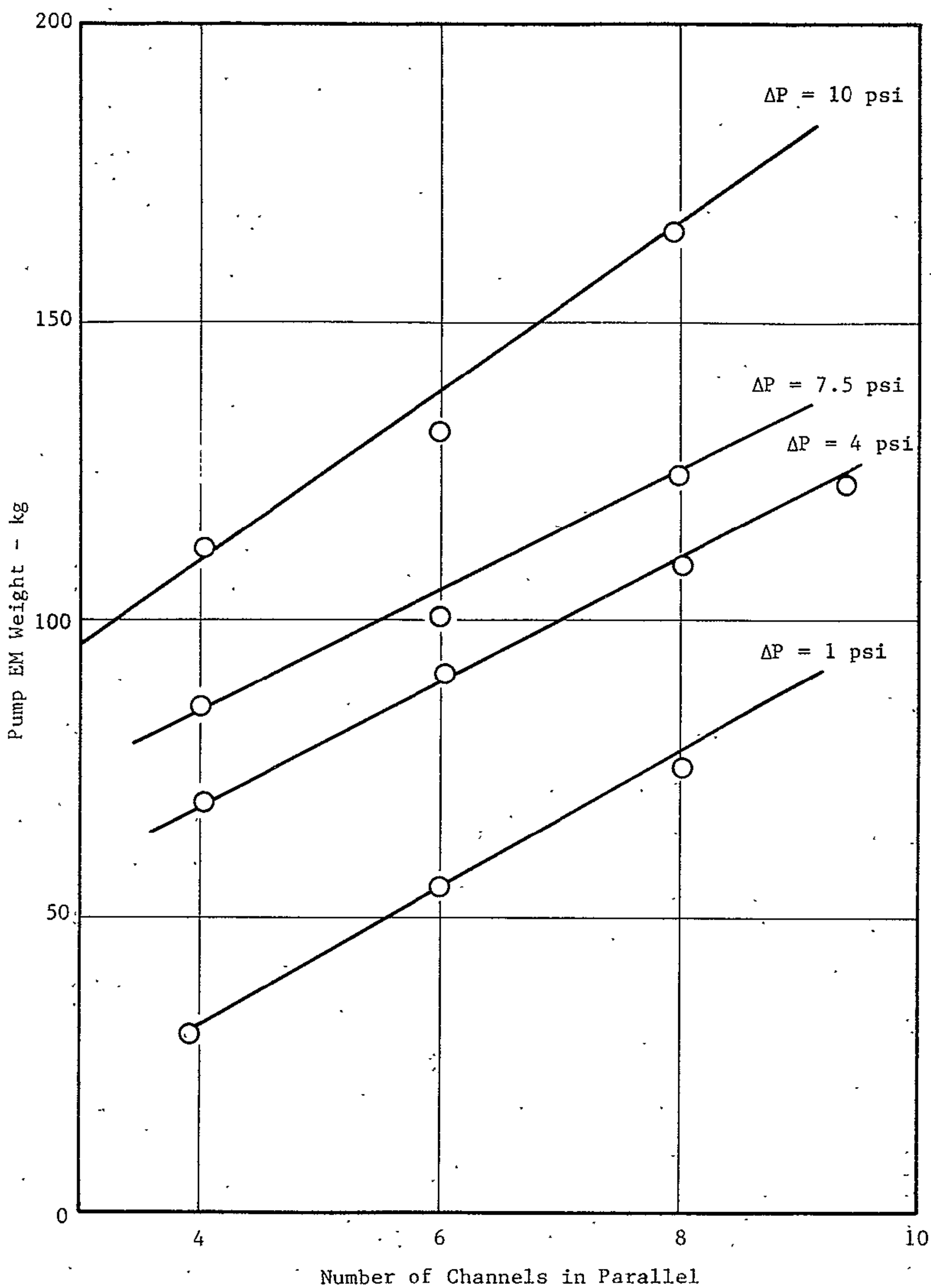



Figure 2-10. Pump Electromagnetic Weight vs Pressure Rise and Number of Channels in Parallel with Flow of 65 cc/sec (0.1 lb/sec) NaK 78 at 1400°F.

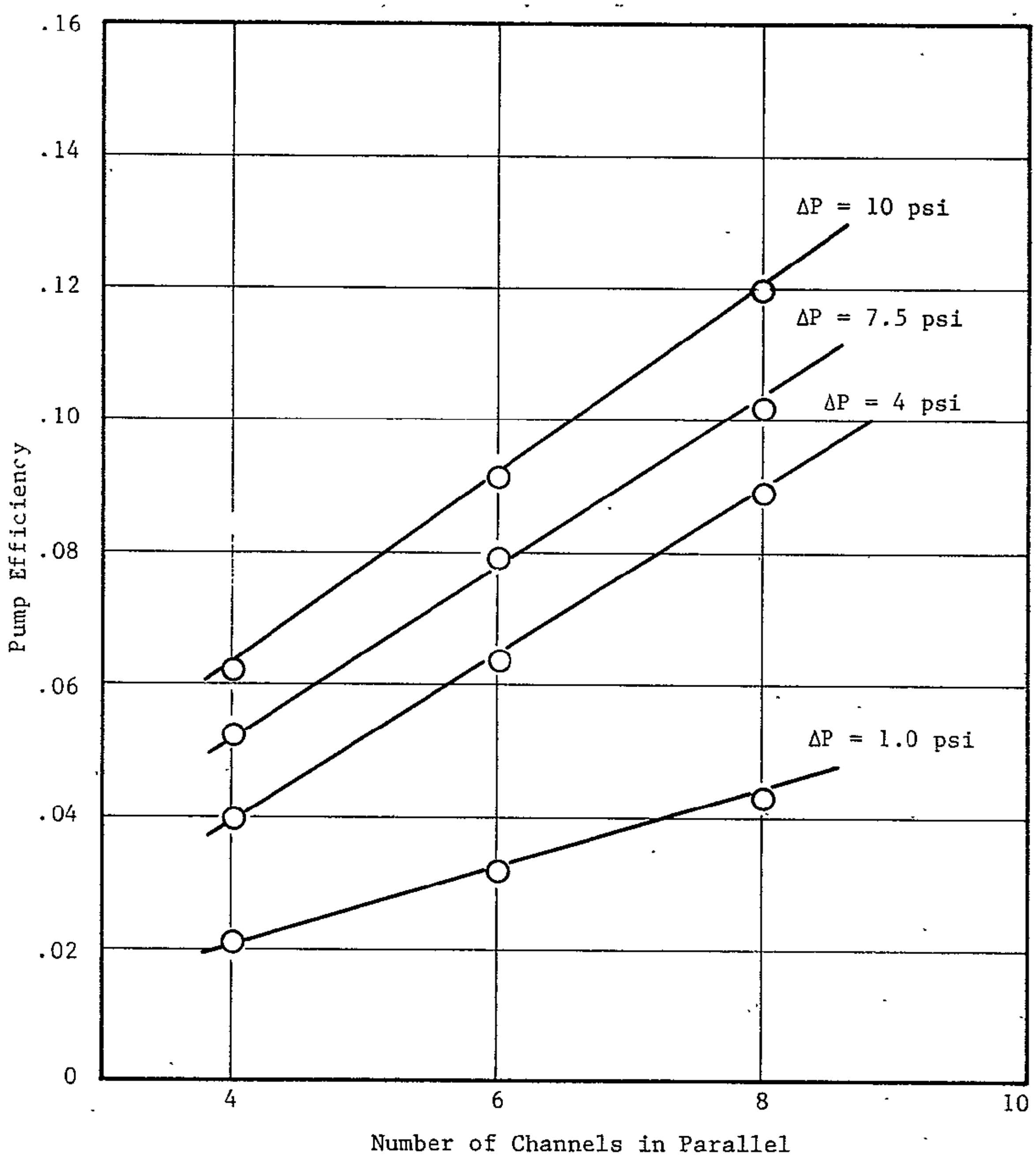



Figure 2-11. Pump Efficiency vs Pressure Rise and Number of Channels in Parallel for Flow of 45 cc/sec (0.07 lb/sec) of NaK 78 at 1400°F.

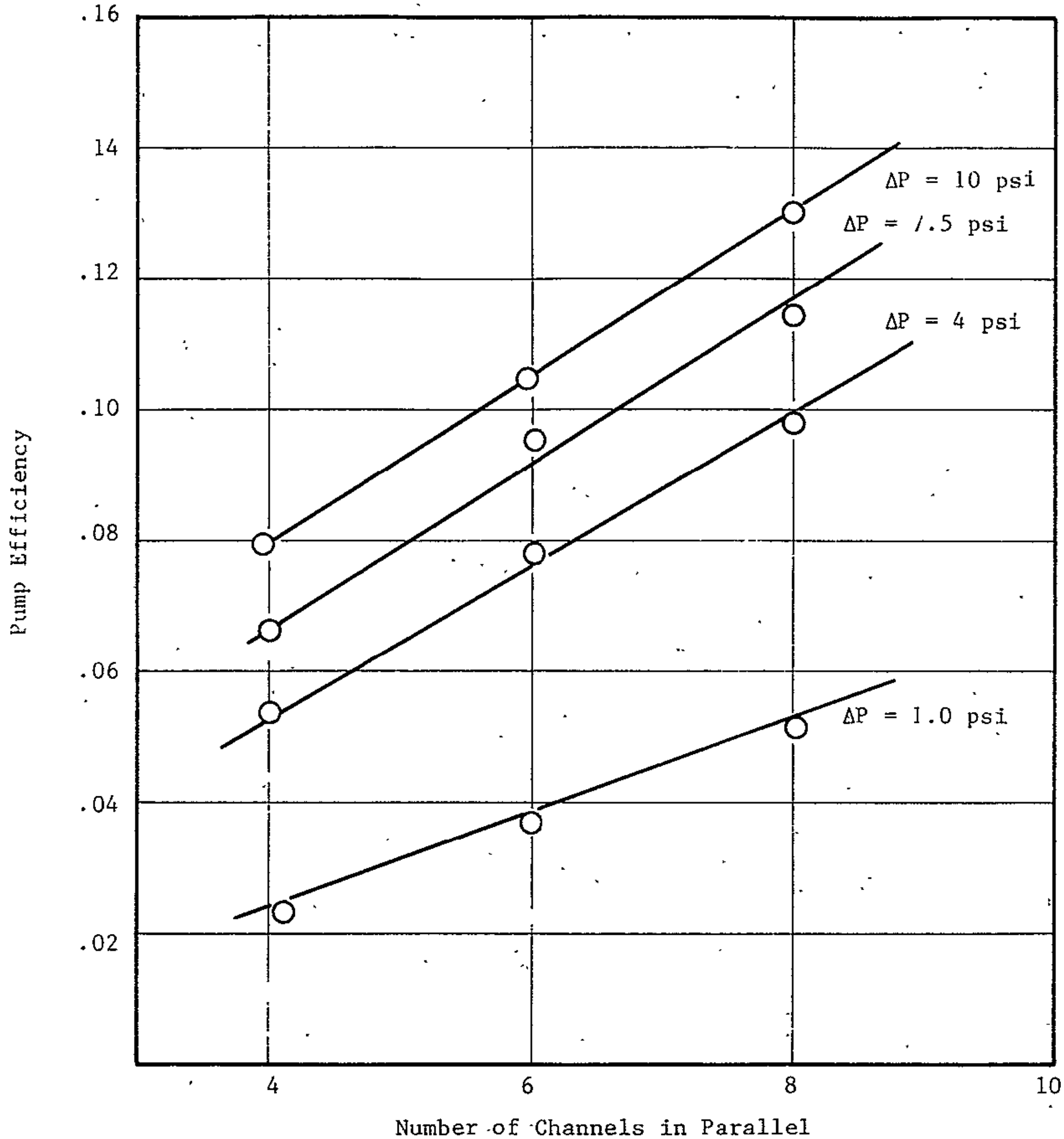



Figure 2-12. Pump Efficiency vs Pressure Rise and Number of Channels in Parallel for Flow of 65 cc/sec (0.1 lb/sec) of NaK 78 at 1400°F.

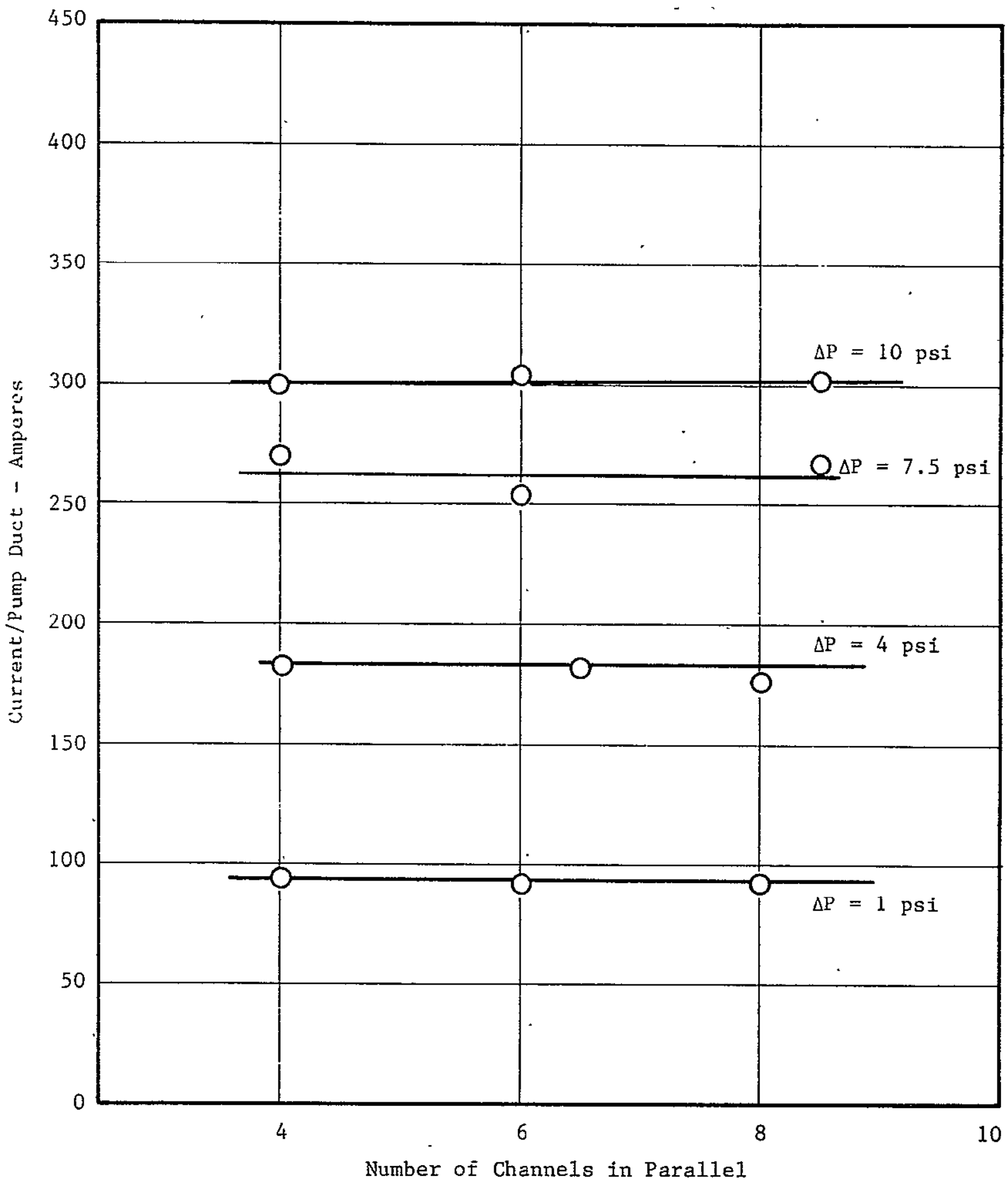



Figure 2-13. Pump Duct Current at Various Pressure Rises and Ducts in Parallel, with Flow of 45 cc/sec (0.07 lb/sec) NaK 78 at 1400°F.

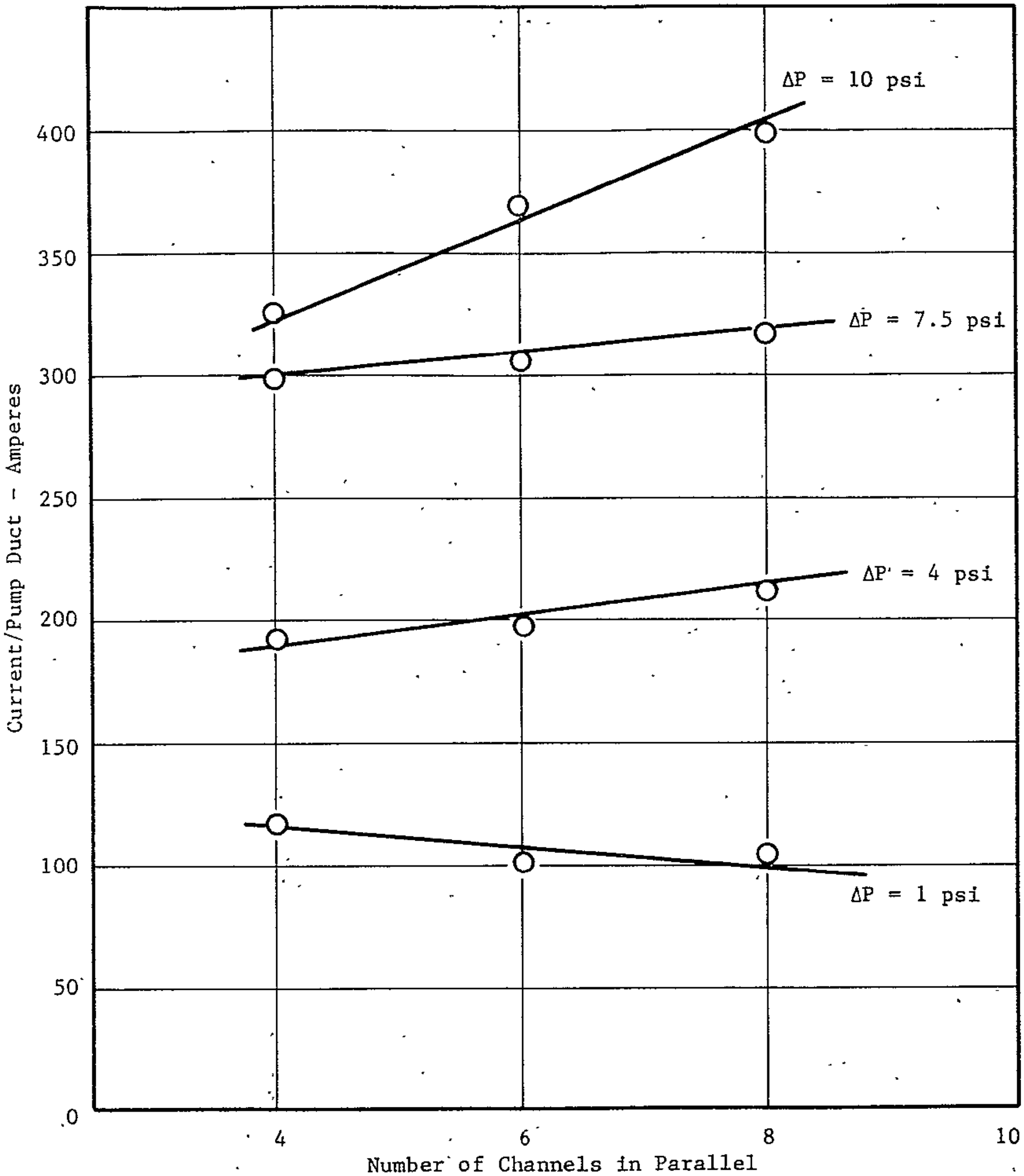



Figure 2-14. Pump Duct Current at Various Pressure Rises and Ducts in Parallel, with Flow of 65 cc/sec (0.10 lb/sec) NaK 78 at 1400°F.

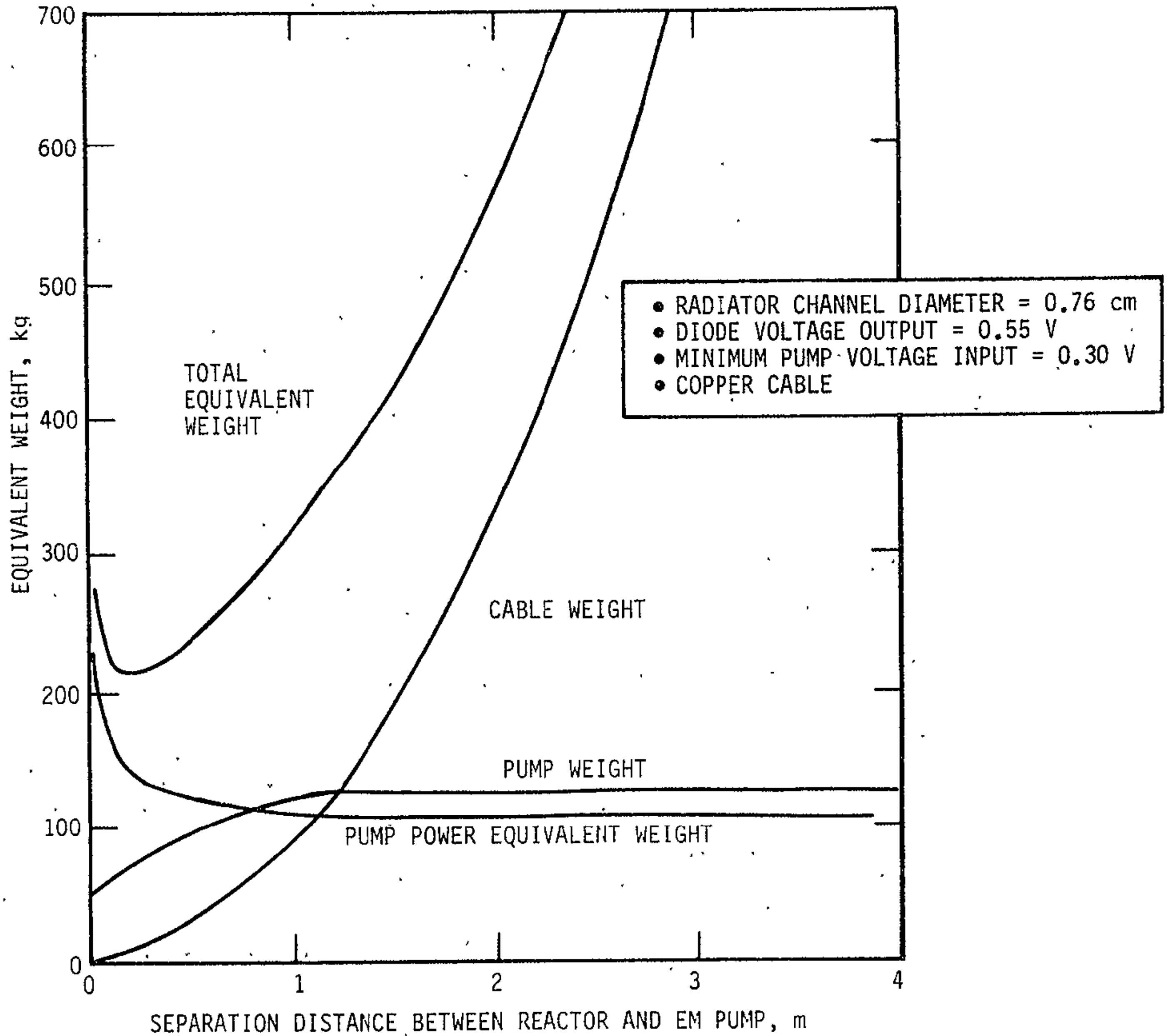
The effect of changing the voltage across the pump from the 0.7 volt design value was assessed. For the case of 45 cc/sec per channel, four channels in parallel, and a 4 psi pressure rise, the pump efficiency is 4 percent at 0.7 v. Decreasing the voltage to 0.5 volts raises the efficiency to 6 percent. This is accomplished by reducing the fraction of the voltage drop across the windings by increasing their size. As a result, the weight of the pump is increased by a factor of 1.6. Similarly, at 0.3 volts a pump efficiency of 10 percent can be achieved at a factor of four penalty in pump weight.

The DC EM pump for the baseline IPD reactor spacecraft is based on a 0.55 v diode output and subsequent pump voltage input of 0.35 v, which corresponds to a 0.61 m separation distance between the IPD reactor and EM pump. For a total heat rejection subsystem pressure drop of approximately $4.8 \times 10^4$ $n/m^2$, a pump weight of 110 kg, pump efficiency of 11 percent, and total pumping power of 7.5 kWe are required. Pump electrical power requirement consists of power to operate the pump, pump low voltage cable losses, and losses of power being conducted through the NaK coolant loop.

In addition, optimum separation distance between the IPD reactor and EM pump was determined by a trade-off between pump low voltage cable losses and pumping power required to overcome electrical losses conducted across the NaK-78 coolant loop. Figure 2-15 presents the results of the EM pump location analysis. Although the minimum weight condition occurs at a separation distance of about 0.2 m, a separation of 0.6 m was permitted to allow for tube and electrical connections between the reactor and pump.

Evaluation of the ducting that connects the IPD reactor and the multi-ducted EM pump has been conducted and is discussed in Reference 6. This effort includes experimental delineation of the ducting arrangement and a preliminary assessment of fabrication feasibility. A one-half scale model of the IPD reactor/EM pump assembly was constructed in order to provide a better understanding of the ducting requirements (Reference 6).

# FIGURE 2-15
# DC EM PUMP LOCATION ANALYSIS
# IPD REACTOR SPACECRAFT



Construction of the model demonstrated that assembly and welding of the ducts to the reactor and the EM pump will be the most difficult part of the fabrication sequence. The EM pump diameter should be as large as possible to maximize the space available for weld operation. It may be desirable to break the EM pump down into several smaller units to provide increased fabrication volume, although this would result in increased weight for the total EM pump system.

Although special fabrication and welding techniques may be required, the assembly does appear to be practical. The welding of the ducts which directly connect the EM pump and the reactor to the radiator may be simplified by fabrication of the EM pump and the TFE units with a portion of this duct in place. This could permit these welding operations to be accomplished at some distance from the EM pump and reactor where more separation between the ducts can be provided. The duct connections between the EM pump and the reactor remain the most difficult due to their close proximity and the limited space. It may be possible to alleviate this to some degree by increasing the spacing between these components. Furthermore, two sample ducts were made up by forming thin walled stainless steel tubes into rectangular cross sections and then brazing and EB welding four of the parts together. The general construction appears quite feasible.

### 2.1.4 Electrical Subsystem

The electrical subsystem of the IPD reactor spacecraft is comprised of low voltage cables that supply power from the IPD reactor to the DC EM pump and the reactor actuator cables. Since the EM pump is powered directly from the reactor leads, there is no need for intermediate hotel power conditioning.

The pump low voltage cable from which 2.55 kWe are lost weighs 47 kg. In comparison, the reactor control drum actuator cable weights and associated power loss are negligible.

### 2.1.5 Support Structure

A structural analysis was performed to evaluate additional structure for the power system of the IPD reactor spacecraft to withstand launch loads imposed by the Titan IIID7/Centaur. A lateral load factor of 1.5 g and axial load factors of 7 g's in the aft direction and 2.5 g's in the forward directions have been established for the launch vehicle (Vol.I, Ref.3-6). By analyzing the sheer and bending moment distribution along the spacecraft, the IPD reactor spacecraft is supported axially and laterally at the bottom section of the neutron shield and laterally at the base, or payload end, of the spacecraft (Figure 2-1).

The additional structure required by power system components is listed in Table 2-3. Total structure weight for the power system is 60 kg.

## 2.2 THRUST SYSTEM

The thrust system, which transfers reactor output power and converts it into propulsive energy, is comprised of the ion engine, high and low voltage cable, and main power conditioning subsystems as well as associated support structure. The thrust system of the IPD reactor spacecraft weighs 838 kg.

### 2.2.1 Ion Engine Subsystem

The ion engine subsystem consists of 30 thrusters, 24 of which are operating at any one time, and the thrust vector control. The ion engine subsystem, being common to all the spacecraft designs, is discussed fully in Volume I, Section 3.5 and is shown in detail in Figure 3.5. Weight of the ion engines and complete thrust vector control system is 213 kg.

### 2.2.2 Low Voltage Cables

The low voltage cables transport 135.7 kWe at 38.2 v reactor output power to the main and special power conditioning units and the payload. The cable material is aluminum except at the reactor outlet where copper is employed because of its higher temperature capability. Figure 2-1 shows the location of the low voltage cables on both sides of the spacecraft as they extend to the power conditioning radiator

TABLE 2-3

SUPPORT STRUCTURE FOR POWER SYSTEM OF

IPD REACTOR SPACECRAFT

| SPACECRAFT COMPONENT | STRUCTURE | SIZE cm | MATERIAL | WEIGHT kg |
|---|---|---|---|---|
| Main Radiator | Stringers | 5x2.5x.13 | Stainless Steel 316 | 25.0 |
| | Frames | 7.6x1.9x.16 | " | 9.7 |
| | Attach-ments | --- | " | 3.3 |
| | Tubes | 2.5x.12 | " | 6.3 |
| | Fittings | --- | " | 6.7 |
| Shield/Shroud Support | Fittings | --- | " | 9.0 |
| Power System | Total | | | 60.0 |

where they branch off to the individual units. The low voltage cable weighs 140 kg and radiates $I^2R$ losses of 5.5 kWe directly to space.

### 2.2.3 High Voltage Cables

The high voltage cables transport 104.4 kWe of 4000 VDC power from the main power conditioners to the ion engines. Total weight of the high voltage leads is 3 kg.

### 2.2.4 Main Power Conditioning

The electrical power system developed for the externally fueled thermionic reactor is shown in Figure 4.2-16. Power is delivered from the two reactor leads at a potential of 40 volts, and is distributed directly to the auxiliary loads, as well as the main power conditioners without being transformed. The main power conditioners convert the 40-volt input to 4000-volt DC for the screen electrodes of the ion thrusters. With individual power conditioners for each thruster, compensation for engine arcing is provided within the control circuit of each conditioner.

The main power conditioner design resulted in a circuit which is 91.6 percent efficient with a specific weight of 2.23 kg/kWe. The component electrical losses and device weight are presented in Tables 2.4 and 2.5, respectively.

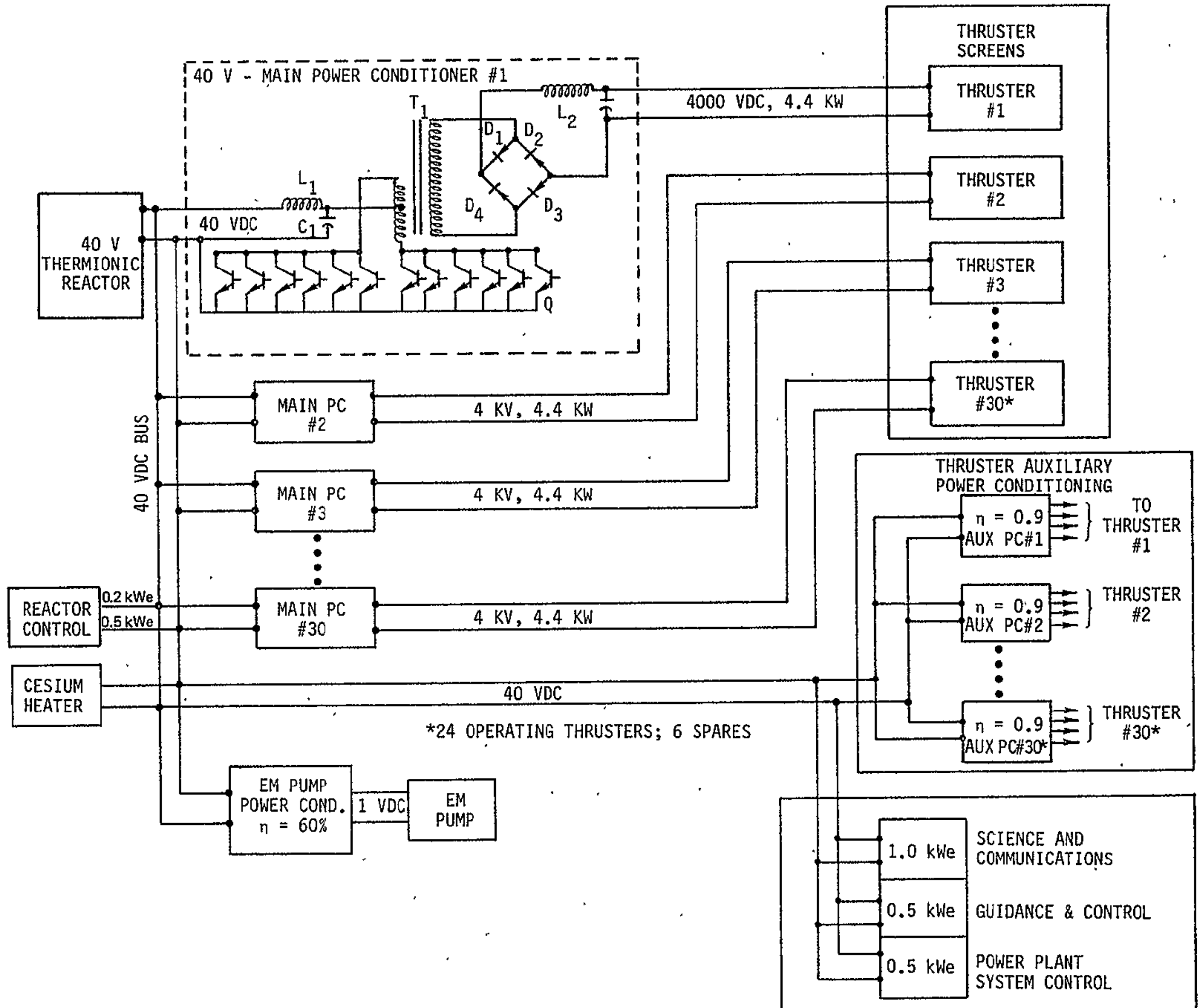
The electrical system design for the externally fueled reactor system is based upon each ion thruster screen being supplied by a separate power conditioner. There are 30 thruster-power conditioner combinations on the spacecraft, six of which are spares.

A power conditioner consists of an inverter to change the low voltage DC output of the thermionic reactor to squarewave AC, a transformer to increase the voltage, and a rectifier to convert the alternating current to direct current.

The output of the reactor is controlled to maintain 40 VDC regardless of load. The thruster screens require approximately 4 kWe at 4000 VDC. Therefore, the power conditioner is required to switch about 100 amperes within the inverter.

FIGURE 2-16

40 VDC THERMIONIC REACTOR ELECTRICAL SYSTEM
EXTERNAL FUEL OR FLASHLIGHT REACTOR DC EM PUMPS



Primarily because of the ratio of input voltage to switch voltage loss, the basic inversion circuit for the power conditioner is selected to be a parallel transistor configuration. The circuit becomes highly efficient through the use of a transistor developed under JPL Contract 952043 and NASA Contract NAS7-400. This high current, low saturation, silicon device has a typical forward saturation loss of less than 0.09 volts for a collector current of 20 amperes.

In order to convert a relatively low voltage to a very high voltage at a high power, two approaches are usually considered. One method is to convert in one module all the power required by the load and provide current sharing among parallel switching transistors. The other method provides multiple modules with individual transformers and few (if any) parallel transistors. Then the transformer secondaries are connected in series to obtain the 4000 volt output. The major advantage of the latter method is that current in sharing in the transistors is forced. With the same current flowing in the in-series secondaries, all primary winding, and hence the transistors, must carry identical currents. Interwinding capacitance and inductance is minimized, allowing faster switching time, hence increased transistor efficiencies. Two important undesirabilities are identified. The first is the problem of circuit operation when a single transistor fails causing the failure of one module. The other drawback is the increased weight for the individual transformers as compared to a single large one. Because of the emphasis on weight and reliability, a single transformer multiple transistor approach is selected.

To meet the necessary current handling capability and to increase the overall efficiency six silicon transistors are switched in parallel. Vol. I, Ref. 2-1 discusses the ramifications of parallel operation of transistors. Basically, the proper control of device characteristics during manufacture, by device selection, and possibly by special circuit techniques, up to 10 power transistors may be successfully operated in parallel.

Primary output voltage regulation is controlled by pulse width modulation of the individual converters. An input filter consisting of an inducer and capacitor, is included in the circuit to function as

# TABLE 2-4

## MAIN POWER CONDITIONER EFFICIENCY SUMMARY NOMINAL 4 kWe UNIT, 40 V INPUT/4 KV OUTPUT

| COMPONENT | LOSSES, WATTS |
|---|---|
| INPUT FILTER | 60.0 * |
| POWER TRANSFORMER | 100.0 |
| TRANSISTOR<br>CONDUCTION 3.45<br>SWITCHING 93.41<br>BASE LOSSES 3.54<br>TOTAL | 100.4 |
| CONNOL CIRCUIT | 65.0 |
| RECTIFIERS | 12.0 |
| OUTPUT FILTER | 30.0 |
| TOTAL | 367.4 |
| EFFICIENCY | 91.6 PERCENT |

*INDUCTOR IN THE INPUT FILTER LIMITS RIPPLE TO ±5 PERCENT. INCREASE OF ALLOWABLE RIPPLE TO ±50 PERCENT, AS EMPLOYED ONLY IN THE 10 VDC INTERNAL FUEL REACTOR PROPULSION SYSTEM DESIGN PERMITS ELIMINATION OF THE INDUCTOR, AND THEREFORE EFFICIENCY INCREASES FROM 91.6 PERCENT TO 93.0 PERCENT. THIS TRANSLATES TO A 16.7 PERCENT REDUCTION IN THE POWER CONDITIONING RADIATOR AREA AND WEIGHT, OR ABOUT 0.13 kg/kWe REDUCTIONS IN PROPULSION SYSTEM SPECIFIC WEIGHT DUE TO THE DECREASED RADIATOR AREA.

# TABLE 2-5

## MAIN POWER CONDITIONER
## WEIGHT SUMMARY
## NOMINAL 4 kWe UNIT, 40V INPUT/4V OUTPUT

| COMPONENT | WEIGHT, KG |
|---|---|
| INPUT FILTER | |
| INDUCTOR | 0.772 * |
| CAPACITOR | 0.091 |
| POWER TRANSFORMER | 2.230 |
| TRANSISTORS (MODIFIED W 1401) | 1.680 |
| CONTROL CIRCUIT | 0.454 |
| RECTIFIERS | 0.091 |
| OUTPUT FILTER | |
| INDUCTOR | 0.136 |
| CAPACITOR | 0.862 |
| WIRE, HARDWARE, ETC. | 2.590 |
| TOTAL WEIGHT | 8.904 |
| DC/DC CONVERTER SPECIFIC WEIGHT, $KG/kWe_{OUT}$ | 2.23 |
| CONVERTER AND RADIATOR SPECIFIC WEIGHT, $KG/kWe_{OUT}$ | 3.50 |

*INDUCTOR IN THE INPUT FILTER LIMITS RIPPLE TO $\pm$ 5 PERCENT. INCREASE TO $\pm$ 50 PERCENT, AS EMPLOYED ONLY IN THE 10 VDC INTERNAL FUEL REACTOR PROPULSION SYSTEM DESIGN PERMITS ELIMINATION OF THE INDUCTOR. THE MAIN PC WEIGHT DECREASES TO 2.03 kg/kWe OUT. THIS CHANGE WOULD RESULT IN A 0.20 kg/kWe DECREASE IN SPECIFIC WEIGHT FOR ALL PROPULSION SYSTEMS BASED ON 40 VDC REACTORS.

an energy storage device during the conduction cycle.

Voltage transformation in a ratio of 1:100 is done with C-core selection material.

A full wave bridge rectifier assembly provides rectification for the 4000 volt alternating current. Because of the high voltage six 800 V diodes are connected in series in each leg of the bridge.

Output filtering limits the screen bus ripple to approximately ten percent.

### 2.2.5 Power Conditioning Radiators

The power conditioning radiator for the IPD reactor spacecraft is a series of 5 bays of 6 panels each, one for each power conditioning unit. The power conditioning radiator rejects waste heat at a maximum surface temperature of 353°K. Also, at the forward end of the power conditioning section there is a narrow radiator from which waste heat generated by the special ion engine power conditioners is rejected.

In order for the main power conditioning radiator to reject 9.6 kWt and the special power conditioning, 0.6 kWt, 5.5 m of radiator length are required. A radiator fin thickness of 0.25 cm and surface emissivity of 0.88 has been assumed. The total power conditioning radiator weight is 96 kg.

### 2.2.6 Support Structure

In conjunction with defining the structural requirements of the power system as outlined in Section 2.1.5, additional structure to maintain the integrity of the thrust system during the launch phase of the mission has been specified. Table 2-6 lists the required structural elements of the thrust system. Total structural weight in the thrust system is 80 kg.

## 2.3 PROPELLANT SYSTEM

The mercury propellant and propellant tank and distribution system are the major components of the propellant system. For the 940-day Comet Halley rendezvous mission as synthesized in Vol. I, Sec. 3.2, the total mercury propellant loading plus a 10 percent ullage allowance is 3660 kg. As shown in Figure 2-1, the mercury propellant is divided

TABLE 2-6

SUPPORT STRUCTURE FOR

THRUST SYSTEM OF IPD REACTOR SPACECRAFT

| SPACECRAFT COMPONENT | STRUCTURE | MATERIAL | WEIGHT kg |
|---|---|---|---|
| Thruster Bay | Skin and Stringers | Aluminum | 47.0 |
| | Beams | " | 7.3 |
| Power Conditioning Radiator | Stringers | Beryllium | 16.0 |
| | Frames | " | 3.0 |
| | Clips | " | 0.7 |
| Base Support | Fittings and Two Struts | " | 6.0 |
| Thrust System | Total | | 80.0 |

into two tanks on either side of the thruster bay. Since the mercury is utilized for gamma shielding, a constant axial thickness of mercury should be maintained throughout the mission. The propellant is stored in a metal bellows and subsequently expelled through the feed lines by action of gas pressure on the bellows. Also, since the center-of-gravity of the spacecraft must be coincident with the center-of-thrust throughout the mission, each tank must contain a nearly equal volume of mercury throughout the mission.

The two cylindrical propellant tanks and feed line system weigh 110 kg. Therefore, the total propellant system weighs 3770 kg.

## 2.4 NET SPACECRAFT

A weight of 662 kg and a power level of 1 kWe have been allocated for net spacecraft in accordance with the mission analysis conducted for the 940-day Comet Halley rendezvous mission. The net spacecraft includes not only the science experiments and instrumentation package, but also the communications equipment and spacecraft guidance and control. For the IPD reactor spacecraft it has been assumed that prior to start-up of the low thrust propulsion system the payload sections can be cantilevered about 1 m axially from the aft end of the spacecraft. This adjustment is necessary to insure that the center-of-gravity of the spacecraft lie in the center of the thruster bay at the start of the mission.

## 2.5 LAUNCH COMPONENTS

This section describes those components that accomplish the integration of the spacecraft to the launch vehicle. A shroud is employed to protect the 1.14 m diameter, 20 m long spacecraft during the launch phase, and an adapter connects the spacecraft to the launch vehicle (Figure 2-1). In addition, the aft section of the shroud is utilized to transmit bending loads from the spacecraft, past the Centaur upper stage, and to the main Titan structure.

After peak heating and maximum dynamic pressure, but before Earth escape is achieved, the forward, cylindrical end of the shroud and the Centaur shroud cover are jettisoned. The corresponding shroud penalty is only 0.08 kg of payload per kg of shroud weight. However, the

middle, conical-shaped shroud remains attached to the spacecraft until Earth escape velocities are achieved, then, it is jettisoned. The penalty for this shroud section is the actual weight of the shroud. For the IPD reactor spacecraft the total flight shroud penalty is 706 kg.

## 3.0 HEAT PIPE COOLED DIODE REACTOR SPACECRAFT

This section is a discussion of the baseline external fuel reactor spacecraft in which each of the reactor diodes is independently cooled by a heat pipe located in the center of the diode. The heat pipe extends the axial length of the diode and emerges from the reactor core where a heat exchanger thermally couples the heat pipes to the primary heat rejection coolant loop. The reactor core is split into two axial sections with heat pipes emerging from the diodes at both ends of the reactor. The two heat exchangers, one at each end of the reactor, are then manifolded to produce a single coolant loop through the main radiator.

A design layout of the heat pipe cooled diode (HCD) reactor spacecraft is presented in Figure 3-1. The 21.9 m long spacecraft has the same basic configuration as the IPD reactor spacecraft. The major design changes from the IPD reactor spacecraft include:

- Beryllium/Stainless steel tube and fin primary radiator
- NaK-78 coolant circulated by AC pumps
- Hotel power conditioning required for AC pumps

Furthermore, a detailed weight summary of the HCD reactor spacecraft presented in Table 3-1. The launch vehicle lift-off requirement of 8411 kg consists of a 657 kg flight shroud weight penalty in addition to the following nuclear electric propulsion spacecraft components at Earth escape:

- Propulsion System 3322 kg
- Mercury Propellant 3660 kg
- Low Thrust Propellant Inerts 110 kg
- Net Spacecraft 662 kg

The low thrust propellant weight, which includes a ten percent ullage factor, and the net spacecraft weight has been specified by the 940-day Comet Halley rendezvous mission analysis ( Vol. I, Sec. 3.2).

TABLE 3-1

# WEIGHT SUMMARY
# BASELINE HCD EXTERNAL FUEL SPACECRAFT

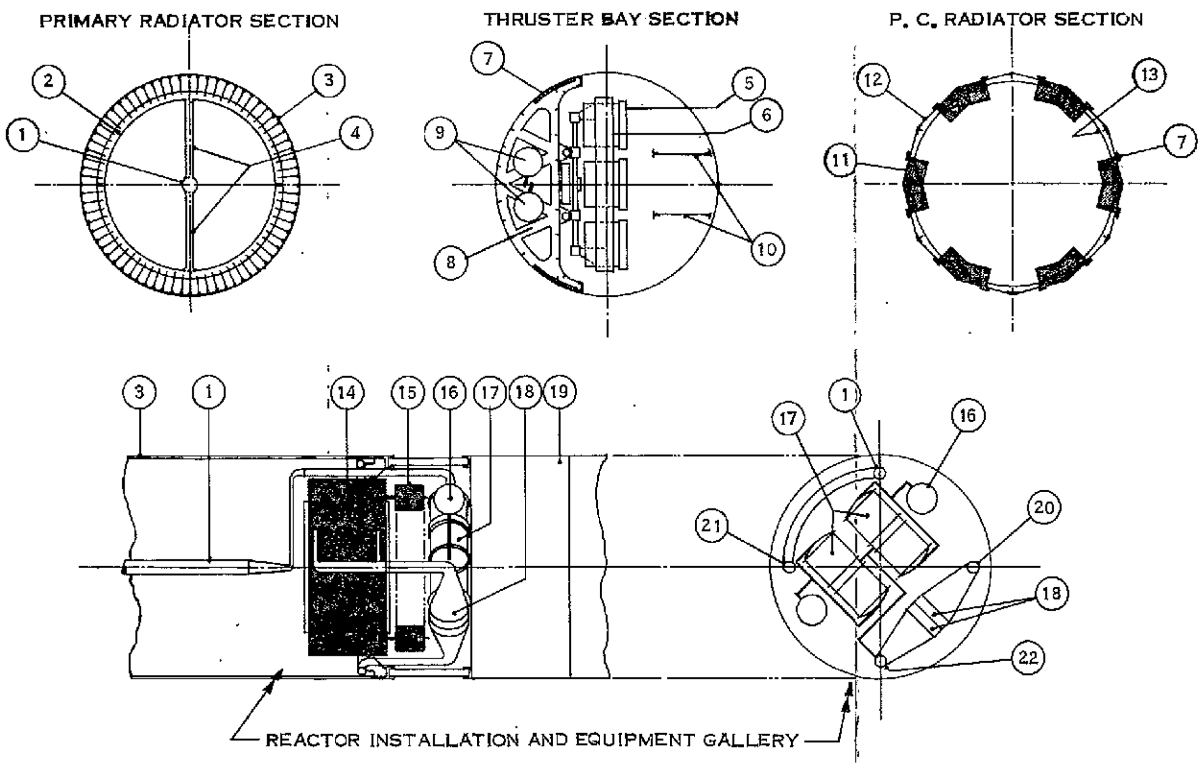
| COMPONENTS | WEIGHT, KG | | |
|---|---|---|---|
| PROPULSION SYSTEM | | | 3322 |
| POWER SYSTEM | | 2490 | |
| REACTOR | 1390 | | |
| HEAT REJECTION | 512 | | |
| NEUTRON SHIELD | 519 | | |
| HOTEL POWER CONDITIONING | 14 | | |
| HOTEL POWER CONDITIONING RADIATOR | 5 | | |
| PUMP LOW VOLTAGE CABLE | 2 | | |
| STRUCTURE | 48 | | |
| THRUST SYSTEM | | 832 | |
| THRUST ARRAY | 213 | | |
| POWER CONDITIONING | 306 | | |
| POWER CONDITIONING RADIATOR | 96 | | |
| LOW VOLTAGE CABLE | 134 | | |
| HIGH VOLTAGE CABLE | 3 | | |
| STRUCTURE | 80 | | |
| PROPELLANT SYSTEM | | | 3770 |
| PROPELLANT | | 3660 | |
| TANKS AND DISTRIBUTION | | 110 | |
| NET SPACECRAFT | | | 662 |
| FLIGHT SHROUD WEIGHT PENALTY | | | 657 |
| LAUNCH VEHICLE PAYLOAD REQUIREMENT | | | 8411 |

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FIGURE 3-1A

# HEAT PIPE COOLED DIODE EXTERNAL FUEL REACTOR SPACECRAFT DESIGN DETAILS




| ITEM DESCRIPTION |
| --- |
| 1. FEED LINE (PRIMARY RADIATOR) |
| 2. FEED HEADER (PRIMARY RADIATOR) |
| 3. PRIMARY RADIATOR |
| 4. MANIFOLD (TO HEADER) |
| 5. ION THRUSTER |
| 6. ION THRUSTER SUPPORT STRUCTURE |
| 7. LOW VOLTAGE CABLES |
| 8. THRUSTER BAY SUPPORT STRUCTURE |
| 9. EXAMPLE MERCURY FLOW CONTROL SYSTEM |
| 10. LAUNCH SUPPORT STRUCTURE |
| 11. MAIN POWER CONDITIONING MODULE |
| 12. POWER CONDITIONING RADIATOR |
| 13. STIFFENING RING |
| 14. REACTOR (EXTERNAL FUEL) |
| 15. REACTOR CONTROL ACTUATORS |
| 16. COOLANT PRESSURIZATION TANK |
| 17. ACCUMULATORS |
| 18. EM PUMPS |
| 19. NEUTRON SHIELD |
| 20. REACTOR INLET LINE |
| 21. REACTOR OUTLET LINE |
| 22. RETURN LINE (PRIMARY RADIATOR) |

The electrical power balance and distribution for the HCD reactor spacecraft is shown in Figure 3-2. Consistent with the other spacecraft designs, the electrical power requirements are based on the value of 120 kWe power input to the thrust system. Approximately 95 percent of the 120 kWe supplies power to the 4000 VDC ion engine screen grid and the remaining 5 percent supplies power to the miscellaneous ion engine loads. The distribution of power throughout the HCD reactor spacecraft is nearly identical to that for the IPD reactor spacecraft. The only differences are that 5.1 $kW_t$ radiates from the low voltage cables, and 2.9 kWe is required for AC pump operation in the HCD reactor spacecraft. Consequently, 130.7 kWe (162.5 kWe, BOL) of reactor output power are required to provide 120 kWe to the thrust system.

## 3.1 POWER SYSTEM

The power system of the HCD reactor spacecraft includes the reactor, neutron shield, main radiator, AC pumps, pump low voltage cable, and the hotel power conditioning. Total weight of the power system is 2490 kg.

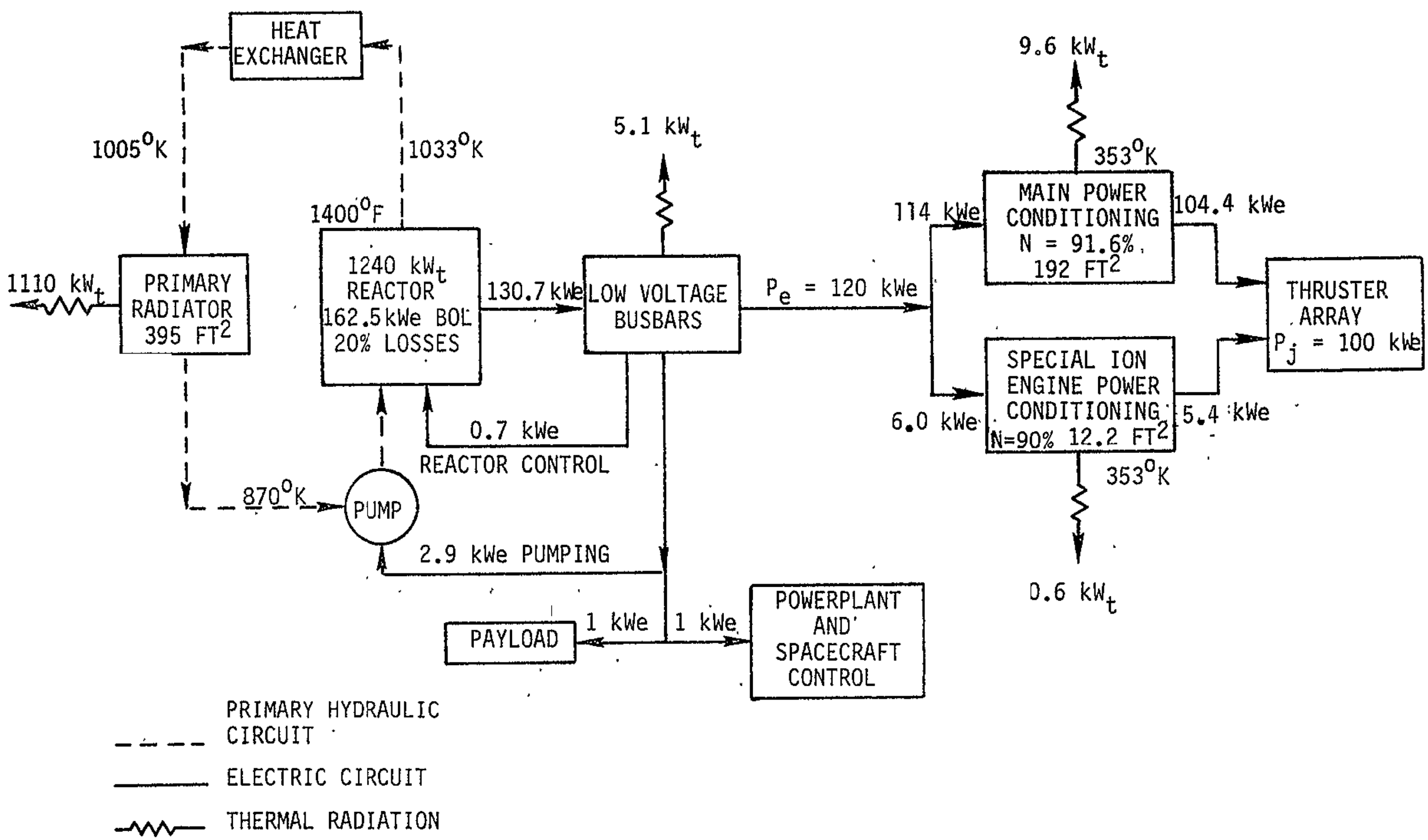
### 3.1.1 Reactor Subsystem

Characteristics of the HCD reactor are based on the performance characteristics of the external fuel reactor as presented in Section 1.1. HCD operating conditions correspond to those selected for the IPD, i.e., diode emitter temperature of 2000°K and collector temperature of 1000°K.

Optimum number of TFE's required to provide 130.7 kWe of reactor output power at a minimum weight was determined from Figure 1-5. The HCD reactor spacecraft design point is characterized by 280 TFE's, which generate 1110 $kW_t$ of reactor waste heat and supply 130.7 kWe of output power at 38.7 v. Decreasing the number of TFE's from the design point value increases heat rejection system weight more significantly than the associated decrease in reactor weight. Conversely, an increase in the number of TFE's from the design point causes the reactor weight to increase more than the associated decrease in heat rejection subsystem weight.

FIGURE 3-2

# EXTERNAL FUEL HEAT PIPE COOLED DIODE SPACECRAFT - 120 kWe POWER BALANCE AND DISTRIBUTION



Characteristics of the external fuel reactor which powers the HCD reactor spacecraft are listed in Table 3-2. The baseline HCD reactor design configuration, based on data from Figure 1-5 is defined by a weight of 1390 kg, reactor diameter of 0.86 m, and individual TFE diameter of 3.7 cm.

### 3.1.2 Shield Subsystem

In accordance with the established guideline for this study, payload and power conditioning electronics has been shielded to neutron and gamma integrated dose limits of $10^{12}$ nvt (En $\geq$ 1 Mev) and $10^{7}$ rads, respectively. Data on which both the neutron and gamma shields are based have been obtained from Reference 2, as a result of analyses conducted by Oak Ridge National Laboratory.

Design of the neutron and gamma shielding for the HCD reactor spacecraft is identical to that for the IPD reactor spacecraft and is discussed fully in paragraph 2.1.2.

### 3.1.3 Heat Rejection Subsystem

The heat rejection subsystem of the HCD reactor spacecraft includes the main radiator, an AC pump, and two heat exchangers on either side of the reactor that thermally couple the reactor diode heat pipes and the main radiator. Reactor waste heat of 1110 kWt is rejected to space by the heat rejection subsystem, which weighs 512 kg. Since the reactor has been designed to accommodate 20 percent diode losses, the main radiator is capable of operating at the more severe end-of-mission thermal load.

#### 3.1.3.1 Main Radiator

Unlike the IPD reactor spacecraft, the main radiator is not directly coupled to the HCD reactor and is, therefore, not affected by the independently cooled diode characteristic of the reactor. Achieving a minimum weight system is the primary criterion in selecting a radiator design. The main radiator has a single coolant loop and consists of beryllium fins and stainless steel tubes. Main radiator and heat exchanger characteristics were determined on the basis of minimum total weight of the main radiator, heat exchanger, and pumping power weight penalty. For the design point reactor coolant outlet temperature

TABLE 3-2

EXTERNAL FUEL REACTOR CHARACTERISTICS
FOR HCD REACTOR SPACECRAFT

| PARAMETER | VALUE |
|---|---|
| Reactor Output Power Capability | |
| BOM | 162.5 kWe |
| EOM | 130.0 kWe |
| Output Voltage | 38.7 |
| Efficiency | 13.4% |
| Number of TFE's | 280.0 |
| Diode Thermal Power | 35.5 w/cm$^2$ |
| Diode Emitter Temperature | 2000$^o$K |
| Diode Collector Temperature | 1000$^o$K |
| Cesium Reservoir Temperature | 620$^o$K |
| TFE Diameter | 3.7 cm |
| Core Radius | 31.1 cm |
| Reactor Radius | 42.8 cm |
| Reactor Weight | 1390 kg |

of 1033$^{o}$K and corresponding temperature drop of 28$^{o}$K through the heat exchanger, main radiator length and weight and primary coolant pressure drop are shown in Figure 3-3 as a function of main radiator coolant temperature drop. At the point of minimum heat rejection subsystem weight, the main radiator weighs 334 kg, is 10.2 m long, has a coolant pressure drop of approximately 3.3 x $10^{4}$ N/m$^{2}$, and temperature drop of 167$^{o}$K.

Optimum main radiator tube and fin configuration is shown in Figure 4.3-4 for overall meteoroid non-puncture probability of 0.95. As a result of the power system structural analysis, discussed in paragraph 3.1.5, the actual main radiator fin thickness was increased to 0.076 cm.

3.1.3.2 <u>Heat Exchanger</u>

The heat exchanger is an integral part of the weight optimization process whereby minimum heat rejection subsystem weight is attained. Figure 3-5 shows heat exchanger weight as a function of temperature drop from the heat pipe to the radiator inlet. Assuming no contact resistance due to electrical insulation in the heat exchanger, the baseline design point of 28$^{o}$K temperature drop and corresponding heat exchanger weight of 42 kg has been selected.

Potential zones of poor contact resistance for the radial conduction of heat out of the heat pipe which impact heat exchanger size and weight, are between the insulator and the heat pipe and. therefore, between the insulator and the metal tube which forms the wall of the coolant channel. The geometry is shown in Figure 3-6. These resistances can be minimized by brazing these two zones together. The identification of the braze material, in terms of its compatibility with the potential vacuum or liquid metal must be evaluated.

Another, but potentially more difficult technique, is to employ a "shrink-fit" technique to joint the heat pipe with the insulator and, similarly, the insulator-pipe assembly with the metal tube of the coolant channel.

Thermal stress must also be considered. It is expected that it will be important to match the coefficient of thermal expansion of the

FIGURE 3-3

# PRIMARY RADIATOR CHARACTERISTICS OF HCD EXTERNAL FUEL REACTOR SPACECRAFT

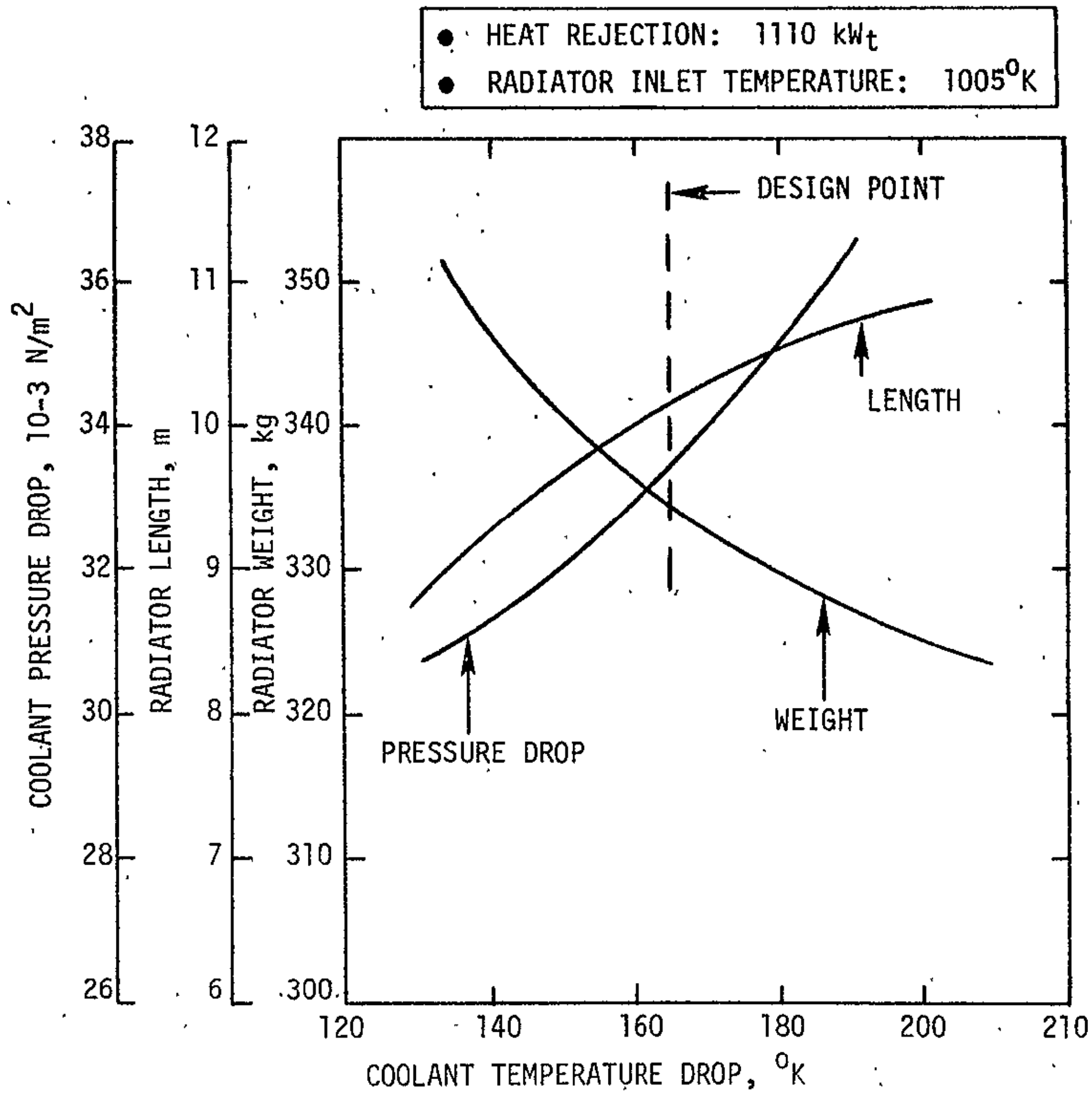
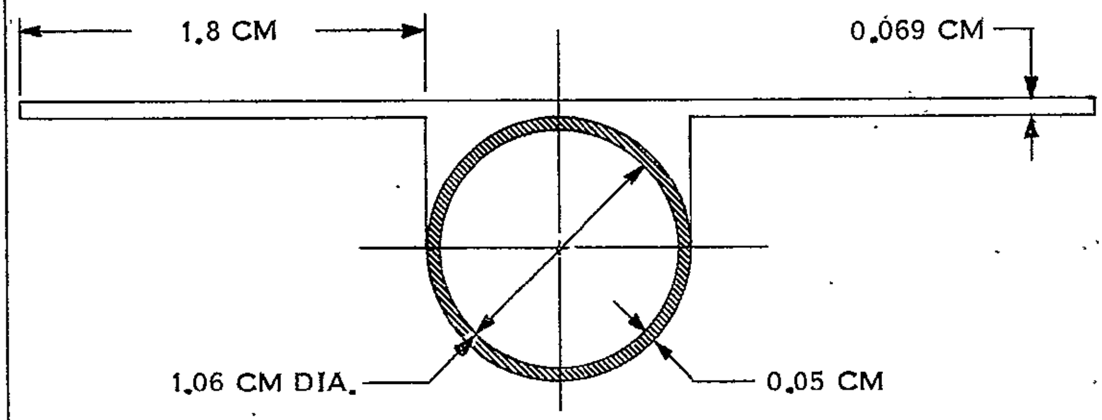


FIGURE 3-4

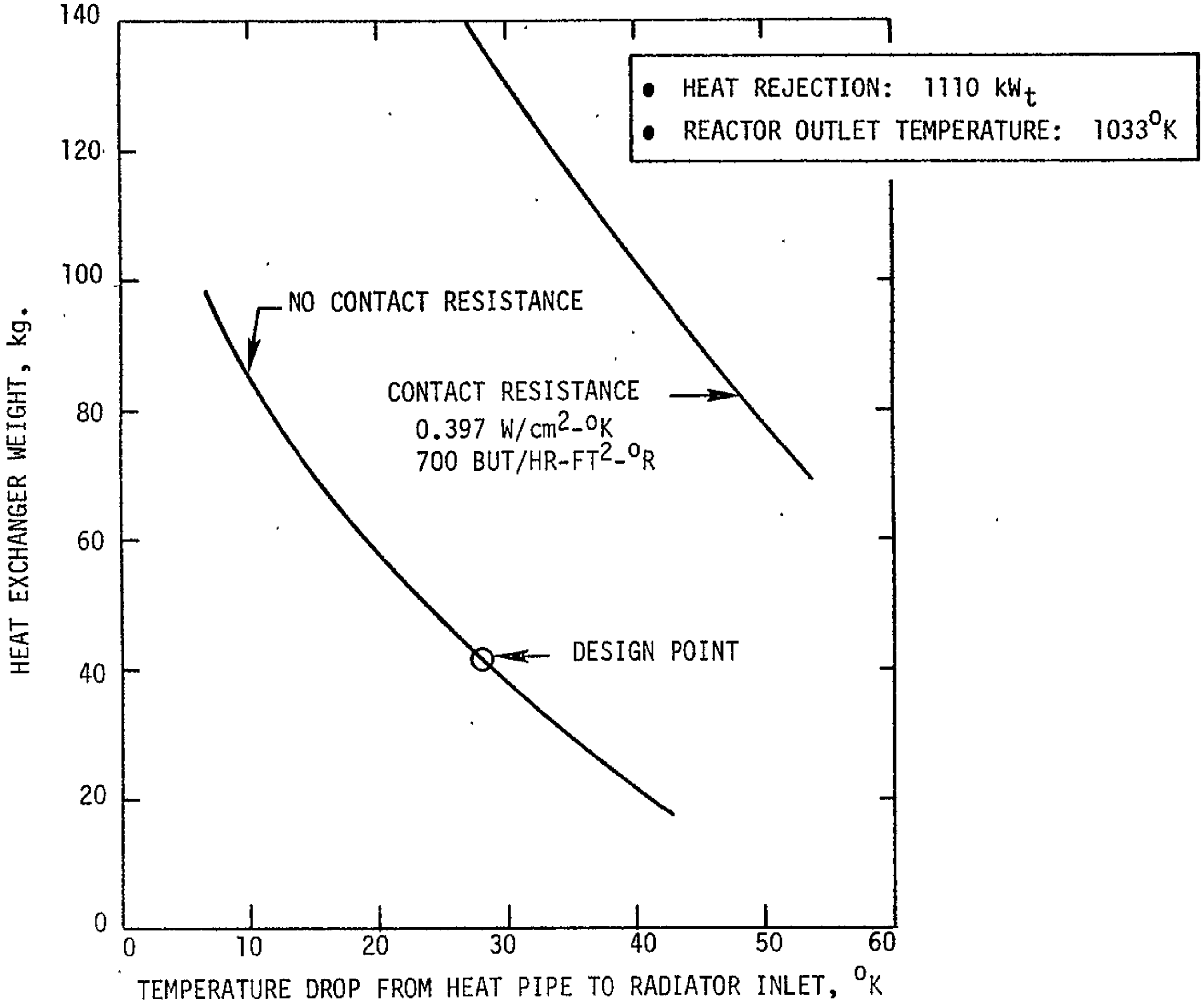
MAIN RADIATOR CHARACTERISTICS
HCD REACTOR SPACECRAFT




| | |
|---|---|
| HEAT REJECTION | 1110 $KW_t$ |
| TEMPERATURE | |
| RADIATOR INLET | 1005°K |
| COOLANT DROP | 28°K |
| RADIATOR LENGTH | 10.2 m |
| RADIATOR DIAMETER | 1.14 m |
| NUMBER OF TUBES | 70 |

FIGURE 3-5

HEAT EXCHANGER CHARACTERISTICS FOR HCD
EXTERNAL FUEL REACTOR SPACECRAFT



metal construction material with that of the alumina or other electrical insulator. If the shrink fit fabrication is used, then the assembly would tend to pull apart, and the thermal contact resistance would adversely increase. For the moderate-temperature application, the expansion coefficient of KOVAR (48 Fe-27Co-25Ni) matches that of alumina up to temperature levels of about 800°K. Columbium would be the choice for higher temperature application. Its expansion coefficient is similar to that of alumina.

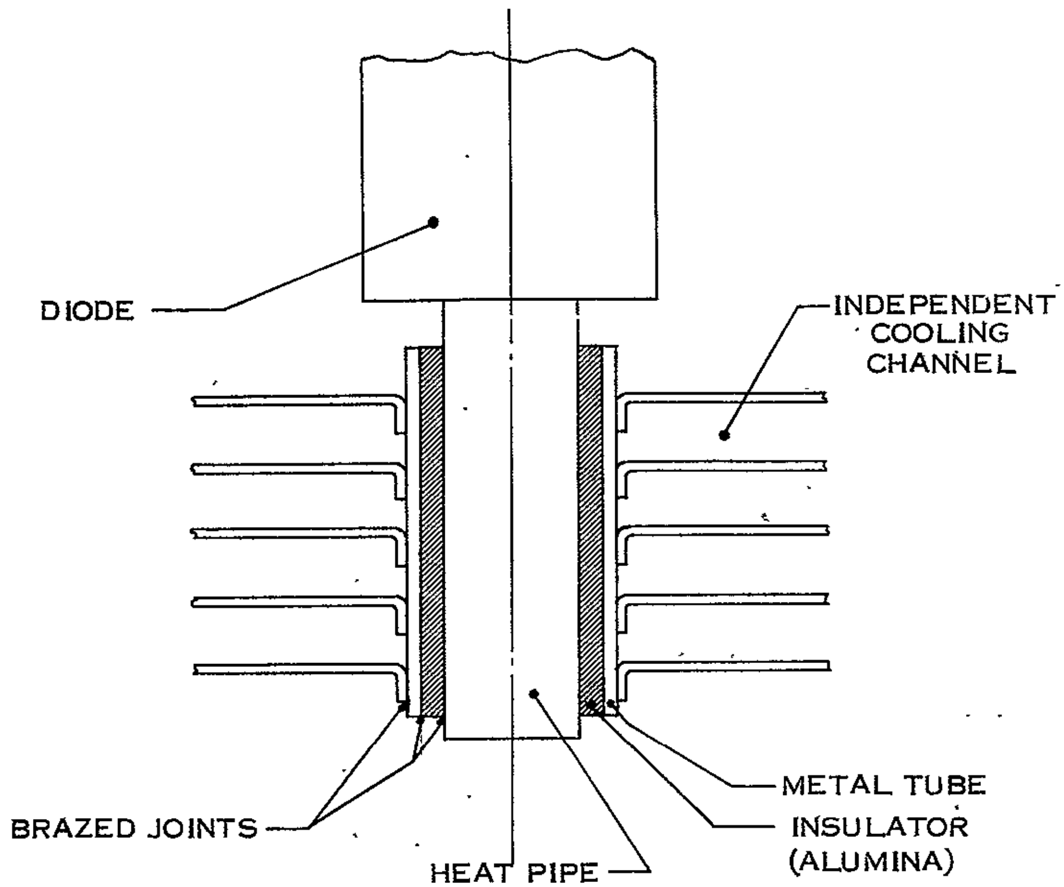
The assembly of the heat exchanger must provide for leak-tight coolant channels, in the event that multiple, redundant cooling loops are required. The preferred design is shown in Figure 3-6. This concept minimizes the number of brazed joints, and provides a continuous surface for good sealing of the insulator to minimize contact resistance. However, internal braze repairs could not be accomplished in this design, in the event of poor braze joint.

#### 3.1.3.3 AC Pump

The baseline HCD reactor spacecraft utilizes an AC pump to circulate NaK-78 in the main radiator. The preference of AC pumps over DC pumps is due mainly to the inefficient power conditioning and extreme low voltage cable losses associated with the fractional voltage input required by the DC pump. The AC pump requires 2.6 kWe input power and weighs 90 kg.

### 3.1.4 Electrical Subsystem

The electrical subsystem provides electrical power required by the hotel components that operate the power system. In the HCD reactor spacecraft the electrical subsystem consists of a power conditioning unit, power conditioning radiator, low voltage cable connecting the reactor and AC pump, and the reactor actuator drives. AC pumps were selected over DC pumps because of the high power conditioning efficiency and lower pump cable losses associated with the AC pump. The hotel power conditioning weighs 14 kg, the power conditioning radiator weighs 5 kg, and the pump cable weighs about 2 kg. For a hotel power conditioning efficiency of 90 percent, the hotel power conditioning radiator rejects 0.3 $Kw_t$ of waste heat.




BASELINE DESIGN IS BASED ON SINGLE
HEAT EXCHANGER COOLANT CHANNEL.
MULTIPLE INDEPENDENT LOOPS CAN BE PROVIDED.

FIGURE 3-6

CONCEPTUAL DESIGN OF HCD SPACECRAFT HEAT EXCHANGER

Weight and power loss of the cables that supply electrical power to the reactor actuator drives are negligible.

#### 3.1.5 Support Structure

Additional structure is required by the spacecraft power system as a result of loads imposed by the Titan IIID7/Centaur during the launch phase of the mission. Definition of the launch environment is provided in Volume I, paragraph 3.4.

For each of the components of the power system, the structural requirements are outlined in Table 3-3. Total additional structure for the power system is 48 kg.

### 3.2 THRUST SYSTEM

The thrust system, which transfers reactor output power and converts it into propulsive energy, is comprised of the ion engine, high and low voltage cable, and main power conditioning subsystems as well as associated support structure. The thrust system of the IPD reactor spacecraft weighs 838 kg.

#### 3.2.1 Ion Engine Subsystem

The ion engine subsystem is identical to that presented in Volume I, Section 3.5.

#### 3.2.2 Low Voltage Cables

The low voltage cables transport 130.7 kWe of 38.7 v reactor output power to the main and special power conditioning units and the payload. The cable material is aluminum except at the reactor outlet where copper is employed because of its higher temperature capability. Figure 3-1 shows the location of the low voltage cables on both sides of the spacecraft as they extend to the power conditioning radiator where they branch off to the individual units. The low voltage cable weighs 134 kg and radiates $I^2R$ losses of 5.1 kWe directly to space. The low voltage cables on the HCD reactor spacecraft are slightly lighter and have lower $I^2R$ losses than those for the IPD reactor spacecraft primarily because of the lower current in the HCD reactor spacecraft cables.

TABLE 3-3

SUPPORT STRUCTURE FOR POWER SYSTEM OF HCD REACTOR SPACECRAFT

| SPACECRAFT COMPONENT | STRUCTURE | MATERIAL | WEIGHT kg |
|---|---|---|---|
| Main Radiator | Frames | Beryllium | 11.0 |
| | Clips | " | 5.6 |
| | Skin | " | 6.0 |
| | Attachments | " | 3.4 |
| Reactor Truss | Tubes | Stainless Steel | 6.3 |
| | Frames and Fittings | " | 6.7 |
| Shield/Shroud Support | Fittings | Aluminum | 9.0 |
| Power System | Total | | 48.0 |

### 3.2.3 High Voltage Cables

The high voltage cables transport 104.4 kWe of 4000 VDC power from the main power conditioners to the ion engines. Total weight of the high voltage leads is 3 kg. The high voltage cable characteristics are identical for both external fuel reactor spacecraft baseline designs.

### 3.2.4 Main Power Conditioning

The main power conditioning is identical with that discussed in paragraph 2.2.4 for the IPD external fuel reactor spacecraft.

### 3.2.5 Power Conditioning Radiator

The power conditioning radiators that reject the 9.6 $kW_t$ of waste heat from the main power conditioning units and the 0.6 $kW_t$ of waste heat from the special ion engine power conditioning units are identical in both the external fuel reactor spacecraft baseline designs. The HCD reactor spacecraft design layout, Figure 3-1, shows that the power conditioning radiator section for the HCD reactor spacecraft is 0.4 m longer than that of the IPD reactor spacecraft. This radiator corresponds to the hotel power conditioning requirements and is part of the electrical network of the power system (paragraph 3.1.3).

### 3.2.6 Support Structure

Support structure for the thrust system of the HCD and IPD reactor spacecraft are identical and has been defined in paragraph 2.2.6.

## 3.3 PROPELLANT SYSTEM

The propellant system is common to all the 120 kWe spacecraft baseline designs and is presented in paragraph 2.3.

## 3.4 NET SPACECRAFT

Net spacecraft is common to all the 120 kWe reactor spacecraft baseline designs and is discussed in paragraph 2.4. For the HCD reactor spacecraft relocations of a portion of the payload is not required to meet the center-of-gravity constraints.

## 3.5 LAUNCH COMPONENTS

The components required for launch of the external fuel reactor spacecraft by a Titan IIID7/Centaur are similar for the two external fuel baseline designs. The launch components are discussed in detail in paragraph 2.5. The flight shroud weight penalty for the HCD reactor spacecraft is 657 kg, which is less than that for the IPD reactor spacecraft. The difference is accounted for by the 1 m fixed payload extension boom that is employed for center-of-gravity adjustment in the IPD reactor spacecraft. This 1 m extension causes the IPD reactor spacecraft to be longer for that section of the shroud which is not jettisoned before Earth escape and, therefore, results in full shroud weight penalty.

# 4.0 ALTERNATE EXTERNAL FUEL REACTOR POWERPLANT STUDIES

A study was conducted to determine the effect on spacecraft design of four alternatives to the baseline powerplant. Perturbations to the baseline designs of the external fuel reactor spacecraft resulted in four alternate designs characterized by the following assumptions:

- Launch by Advanced Logistics Shuttle (ALS)
- U-233 fueled external fuel reactor
- Use of DC EM pumps in primary heat rejection system
- Multiple coolant loops in main radiator

DC EM pumps are used in the IPD reactor spacecraft baseline design. Multiple coolant loops are not compatible with the IPD concept. Therefore, the last two alternative designs will not be considered for the IPD reactor spacecraft. Each of the candidate alternate spacecraft designs will be discussed in the following paragraphs.

## 4.1 ALS-LAUNCHED EXTERNAL FUEL REACTOR SPACECRAFT

The two baseline external fuel reactor spacecraft have been reconfigured for launch by the ALS. The major constraint imposed by the ALS is that the usable payload bay is 18.3 m long, which is shorter than either of the baseline external fuel reactor spacecraft designs. An alternate to each baseline design has been generated by constricting the spacecraft length to 18.3 m without folding the spacecraft or relying on in-orbit assembly of the spacecraft sections.

Basically, in order to shorten the spacecraft to the 18.3 length, the spacecraft diameter is increased. Commensurate effects on the spacecraft design include the following factors:

- Addition of tungsten permanent gamma shielding since increase in spacecraft diameter diminishes effect of mercury propellant as gamma shield, for the fixed mercury propellant inventory.
- Increase in neutron shield weight as spacecraft diameter increases.
- Heat rejection subsystem weight decreases for the IPD reactor spacecraft due to shorter radiator and longer coolant tube diameter.
- Heat rejection subsystem weight increases for the HCD reactor spacecraft, corresponding to a change in main radiator temperature conditions to effect part of the length constriction.
- Decrease in primary heat rejection subsystem pumping power due to shorter main radiator.
- Low voltage cable weight and electrical losses decrease due to the shorter power conditioning radiator.
- Less support structure is required as a result of decreased spacecraft length, and a less severe launch environment.
- Reactor output power decreases with decrease in pumping power requirements and electrical losses.
- Propulsion systems specific weight increases because of the dominating effect of additional neutron and gamma shielding.
- Although spacecraft weight increases, total launch weight decreases since no flight shroud penalty is required.

The thermal conditions of the main radiator of the HCD reactor spacecraft have been changed from the baseline radiator temperature drop of $167^{\circ}K$ and a heat exchanger temperature drop of $28^{\circ}K$, to an ALS design radiator temperature drop of $139^{\circ}K$ and heat exchanger temperature drop of about $6^{\circ}K$. The weight penalty associated with the change in main radiator conditions is less severe than that obtained by solely increasing spacecraft diameter to meet the total spacecraft length limitations.

The effect of spacecraft length on spacecraft diameter, propulsion system weight, and propulsion system specific weight is presented in Figure 4-1 for the IPD reactor spacecraft, and on Figure 4-2 for the HCD reactor spacecraft. Also, a comparison of the baseline design and the ALS launched design of the IPD reactor spacecraft is made in Table 4-1. To reconfigure the baseline IPD reactor spacecraft for launch by the ALS, the spacecraft diameter increases from 1.14 m to 1.31 m, and the propulsion system specific weight is increased by 2 kg/kWe. Reactor power output, however, decreases from a baseline value of 135.7 kWe to 132.7 kWe, which primarily reflects the reduced pumping power required for the ALS launch configuration. Since decreasing spacecraft length accentuates the center-of-gravity problem in the IPD reactor spacecraft, the net payload of the ALS-launched spacecraft must be extended an additional 1.1 m from the aft end of the spacecraft.

Table 4-2 shows the comparison between the baseline and the ALS-launched configurations of the HCD reactor spacecraft. The result of constraining the baseline spacecraft design to a length of 18.3 m is the increase in spacecraft diameter from 1.14 m to 1.43 m which results in an increase in propulsion system specific weight of 1.7 kg/kWe, and a decrease in reactor output power to 130.4 kWe. Most of the length decrease was accomplished by decreasing main radiator length by means of increasing the baseline temperature drops across the main radiator and heat exchangers. Therefore, power system weight increased 210 kg. Also, to satisfy the center-of-gravity constraint, the net payload must be boomed approximately one meter from the spacecraft.

### 4.2 U-233 FUELED EXTERNAL FUEL REACTOR SPACECRAFT

This paragraph discusses the alternate spacecraft design that results when U-235 fueled baseline reactors are replaced by reactors fueled with U-233. Characteristics of the U-235 and U-233 fueled reactor diodes are presented in paragraph 1.0. The only difference in both external fuel baseline spacecraft designs that are fueled with U-233 is that reactor size and weight are significantly less for the U-233 fueled reactors.

FIGURE 4-1

EFFECT OF SPACECRAFT LENGTH ON EXTERNAL FUEL IPD REACTOR SPACECRAFT WEIGHT AND DIAMETER

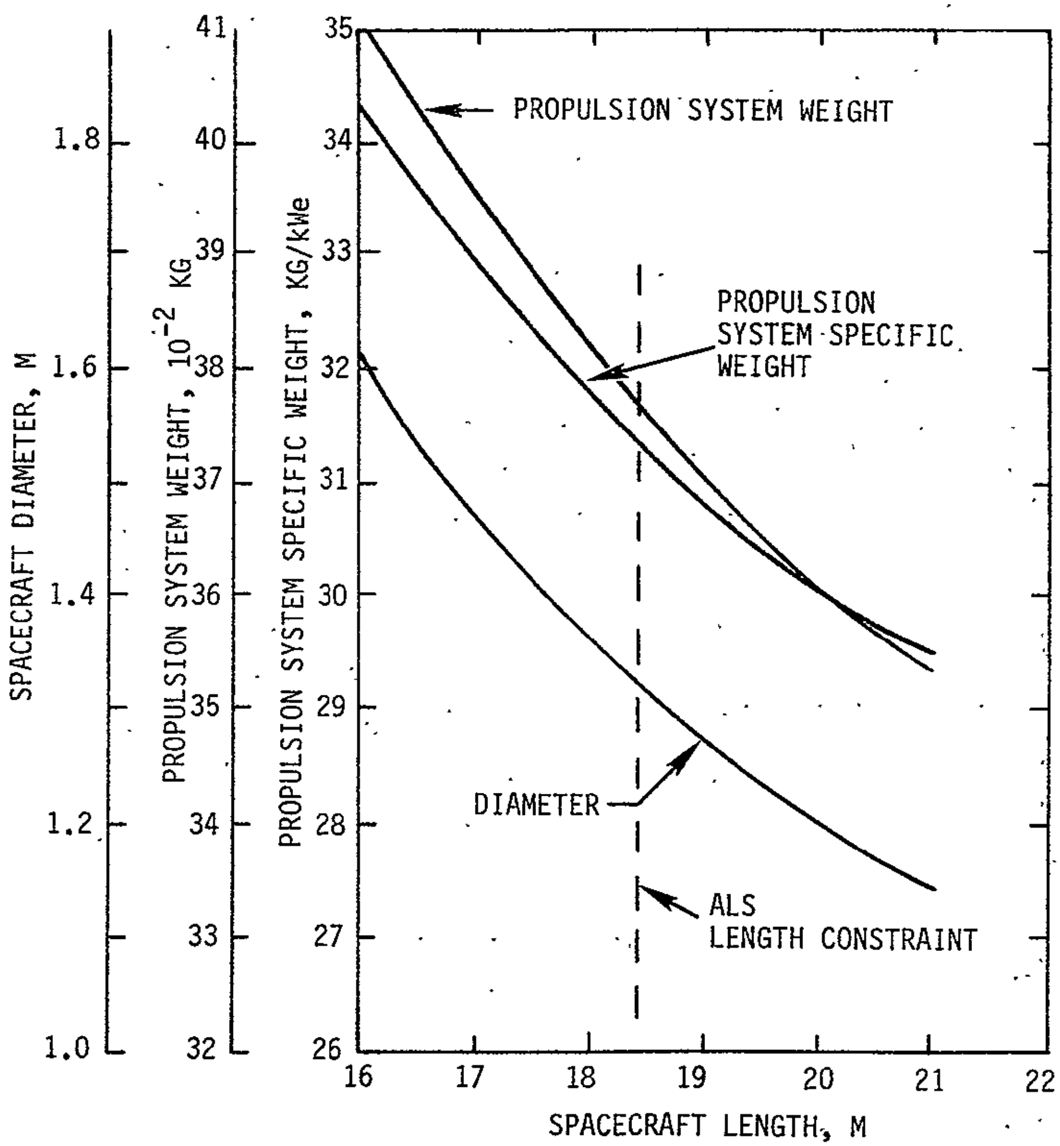


FIGURE 4-2

EFFECT OF SPACECRAFT LENGTH ON EXTERNAL FUEL HCD REACTOR SPACECRAFT WEIGHT AND DIAMETER

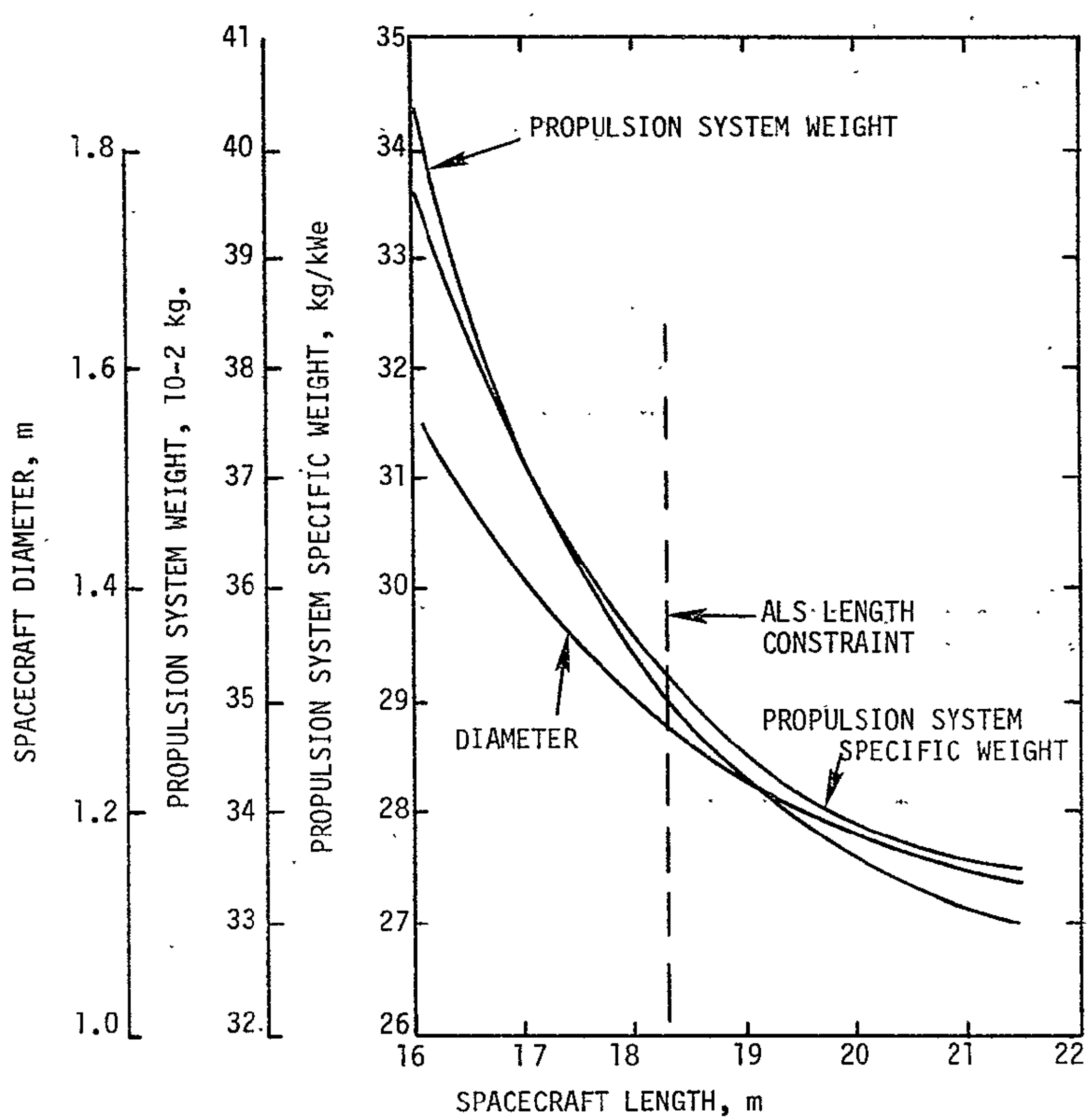


TABLE 4 - 1

IPD EXTERNAL FUEL REACTOR SPACECRAFT

Comparison of The Baseline Design with the ALS Launched Design

| PARAMETER | BASELINE DESIGN | | ALS LAUNCHED DESIGN | |
|---|---|---|---|---|
| Spacecraft Length, m. | | 21.0 | | 18.3 |
| Spacecraft Diameter, m. | | 1.14 | | 1.31 |
| **Weights, kg** | | | | |
| Propulsion System | | 3552 | | 3797 |
| Power Subsystem | 2714 | | 2967 | |
| Thruster Subsystem | 838 | | 830 | |
| Propellant System | | 3770 | | 3770 |
| Net Spacecraft | | 662 | | 662 |
| Flight Shroud Weight Penalty | | 706 | | NONE |
| Launch Weight Requirement | | 8690 | | 8229 |
| Propulsion System Specific Weight, kw/kWe | | 29.6 | | 31.6 |
| Electrical Power Usage, kWe | | | | |
| Gross Reactor Power Output | | 135.7 | | 132.7 |
| Spacecraft Loads | 117.35 | | 115.53 | |
| Electrical System Losses | 18.35 | | 17.17 | |
| Payload Distribution | | | | |
| Percent in Forward Bay | | NONE | | NONE |
| Percent at End of Spacecraft | | 100 (Boomed 1.0m) | | 100 (Boomed 2.1m) |

TABLE 4 - 2

HCD EXTERNAL FUEL REACTOR SPACECRAFT

Comparison of the Baseline Design with the ALS Launched Design

| PARAMETER | BASELINE DESIGN | | ALS LAUNCHED DESIGN | |
|---|---|---|---|---|
| Spacecraft Length, m. | | 21.9 | | 18.3 |
| Spacecraft Diameter,m. | | 1.14 | | 1.43 |
| Weights, kg | | | | |
| Propulsion System | | 3322 | | 3525 |
| Power Subsystem | 2490 | | 2700 | |
| Thruster Subsystem | 832 | | 825 | |
| Propellant System | | 3770 | | 3770 |
| Net Spacecraft | | 662 | | 662 |
| Flight Shroud Weight Penalty | | 657 | | NONE |
| Launch Weight Requirements | | 8711 | | 7957 |
| Propulsion System Specific Weight, kw/kWe | | 27.7 | | 29.4 |
| Electrical Power Usage, kWe | | | | |
| Gross Reactor Power Output | | 130.7 | | 130.4 |
| Spacecraft Loads | 114.98 | | 114.74 | |
| Electrical System Losses | 15.72 | | 15.66 | |
| Payload Distribution | | | | |
| Percent in Forward Bay | | NONE | | NONE |
| Percent at End of Spacecraft | | 100 | | 100 (Boomed 1.0m) |

Comparison of the U-233 fueled reactor spacecraft with the baseline design is shown in Table 4-3 for the IPD reactor spacecraft. Utilization of U-233 fuel results in a decrease in reactor weight of 485 kg and corresponding decrease in propulsion system specific weight of 4.1 kg/kWe. This decrease in weight near the forward end of the spacecraft necessitates a shift of 20 percent of net payload from the aft payload bay to the forward bay, located between the aft mercury propellant tank and the hotelpower conditioning radiator.

Similarly, comparison of the U-233 fueled reactor spacecraft with the baseline-HCD spacecraft design is presented in Table 4-4. A reactor weight decrease of 480 kg and propulsion system specific weight decrease of 4 kg/kWe is realized with a U-233 fueled HCD reactor. The center-of-gravity constraint is satisfied by relocating approximately 30 percent of the net payload to the forward payload bay.

## 4.3 USE OF DC EM PUMP IN EXTERNAL FUEL REACTOR SPACECRAFT

Since the IPD reactor spacecraft baseline design utilizes a DC EM pump in the primary heat rejection subsystem, only the HCD reactor spacecraft where the baseline AC pumps are replaced by DC pumps will be discussed as an alternate design. Replacing AC pumps with DC pumps results in the following changes in the spacecraft design:

- Heat rejection subsystem weight decreases primarily because DC pumps are lighter than AC pumps for comparable performance.
- Hotel power conditioning unit and radiator weights increase because of the comparatively inefficient power conditioning from 40 VDC to 1 VDC required by the DC pump.
- The pump low voltage cable is required to provide pump power at only 1 to 2 volts, and is therefore, heavy and results in relatively high power losses.
- The main low voltage cable weight and power loss increases as a result of the longer power conditioning radiator section.
- Support structure increases with the longer spacecraft length.
- Reactor output power increases primarily due to larger power conditioning and low voltage cable losses.

TABLE 4 - 3

IPD EXTERNAL FUEL REACTOR SPACECRAFT

Comparison of U-235 Fueled Baseline with the U-233 Fueled Design

| PARAMETER | BASELINE DESIGN | | U-233 FUELED DESIGN | |
|---|---|---|---|---|
| Spacecraft Length, m. | | 21.0 | | 20.0 |
| Spacecraft Diameter, m. | | 1.14 | | 1.14 |
| **Weights, kg** | | | | |
| Propulsion System | | 3552 | | 3067 |
| Power Subsystem | 2714 | | 2229 | |
| (Reactor) | (1410) | | (925) | |
| Thruster Subsystem | 838 | | 838 | |
| Propellant System | | 3770 | | 3770 |
| Net Spacecraft | | 662 | | 662 |
| Flight Shroud Weight Penalty | | 706 | | 706 |
| Launch Weight Requirement | | 8690 | | 8205 |
| Propulsion System Specific Weight, kw/kWe | | 29.6 | | 25.5 |
| **Electrical Power Usage, kWe** | | | | |
| Gross Reactor Power Output | | 135.7 | | 135.7 |
| Spacecraft Loads | 117.35 | | 117.35 | |
| Electrical System Losses | 18.35 | | 18.35 | |
| **Payload Distribution** | | | | |
| Percent in Forward Bay | | NONE | | 20 |
| Percent at End of Spacecraft | | 100 (Boomed 1.0m) | | 80 |

TABLE 4 - 4

HCD EXTERNAL FUEL REACTOR SPACECRAFT

Comparison of U-235 Fueled Baseline with the U-233 Fueled Design

| PARAMETER | BASELINE DESIGN | | U-233 FUELED DESIGN | |
|---|---|---|---|---|
| Spacecraft Length, m. | | 21.9 | | 21.9 |
| Spacecraft Diameter, m. | | 1.14 | | 1.14 |
| Weights, kg | | | | |
| Propulsion System | | 3322 | | 2842 |
| Power Subsystem | 2490 | | 2010 | |
| (Reactor) | (1390) | | (910) | |
| Thruster Subsystem | 832 | | 832 | |
| Propellant System | | 3770 | | 3770 |
| Net Spacecraft | | 662 | | 662 |
| Flight Shroud Weight Penalty | | 657 | | 657 |
| Launch Weight Requirement | | 8411 | | 7892 |
| Propulsion System Specific Weight, kw/kWe | | 27.7 | | 23.7 |
| Electrical Power Usage, kWe | | | | |
| Gross Reactor Power Output | | 130.7 | | 130.7 |
| Spacecraft Loads | 114.98 | | 114.98 | |
| Electrical System Losses | 15.72 | | 15.72 | |
| Payload Distribution | | | | |
| Percent in Forward Bay | | NONE | | 30 |
| Percent at End of Spacecraft | | 100 | | 70 |

A summary of the comparison between spacecraft designs using an AC pump and a DC pump is provided in Table 4-5. Using DC pumps in the HCD reactor spacecraft increases spacecraft length from 21.9 m to 23.5 m, and increases propulsion system specific weight by 0.6 kg/kWe. Reactor output must be increased from 130.7 kWe to 135.3 kWe. Relocation of 10 percent of the payload to the forward bay is also required. Table 4-6 presents a comparison of some of the more detailed characteristics of the AC and DC pumps and associated equipment. The primary differences, as indicated in Table 4-6 are hotel power conditioner efficiency, 90 percent for AC pumps and 60 percent for DC pumps, and pump cable weight, 2 kg for AC pumps and 82 kg for DC pumps.

## 4.4 MULTIPLE RADIATOR LOOPS IN EXTERNAL FUEL REACTOR SPACECRAFT

The alternate design considered in this paragraph is the HCD reactor spacecraft where the baseline single loop main radiator loop has been replaced by four independent loops, one of which is redundant. This perturbation was not made to the baseline IPD reactor spacecraft because it is basically contrary to the IPD concept.

Determination of a minimum weight configuration was accomplished by selecting those heat rejection characteristics that resulted in a minimum combined weight of the heat exchangers, four-loop main radiator, and pumping power weight penalty. Characteristics of the four-loop main radiator are presented in Figure 4-3 as a function of temperature drop through the radiator and through the heat exchanger. The single loop heat rejection system design point is also indicated on Figure 4-3 for comparison. Replacing the single coolant loop with the four independent coolant loops in the main radiator resulted in the following changes to the baseline HCD reactor spacecraft:

- Heat rejection subsystem weight increases primarily due to the increased radiator area associated with the redundant loop.
- Optimum heat exchanger temperature drop decreases from $28^{o}K$ to $5.5^{o}K$.
- Optimum main radiator temperature drop decreases from $167^{o}K$ to $139^{o}K$.

TABLE 4-5

COMPARISON OF AC PUMP AND DC PUMP
CONFIGURATIONS OF HCD REACTOR SPACECRAFT

| Parameters | Baseline Design | | Design Using DC Pumps | |
|---|---|---|---|---|
| Spacecraft Length, m | | 21.9 | | 23.5 |
| Spacecraft Diameter, m | | 1.14 | | 1.14 |
| Spacecraft Weight, kg | | | | |
| Propulsion System | | 3322 | | 3391 |
| Power System | 2490 | | 2538 | |
| Thrust System | 832 | | 853 | |
| Propellant System | | 3770 | | 3370 |
| Net Spacecraft | | 662 | | 662 |
| Flight Shroud Penalty | | 657 | | 730 |
| Total Launch Weight | | 8411 | | 8553 |
| Propulsion System Specific Weight kg/kWe | | 27.7 | | 28.3 |
| Electrical Power Distribution, kWe | | | | |
| Reactor Power Output | | 130.7 | | 135.3 |
| Spacecraft Loads | 114.98 | | 115.07 | |
| Electrical Losses | 15.72 | | 20.23 | |
| Payload Distribution | | | | |
| Percent in Forward Bay | | 0 | | 10 |
| Percent at End of Spacecraft | | 100 | | 40 |

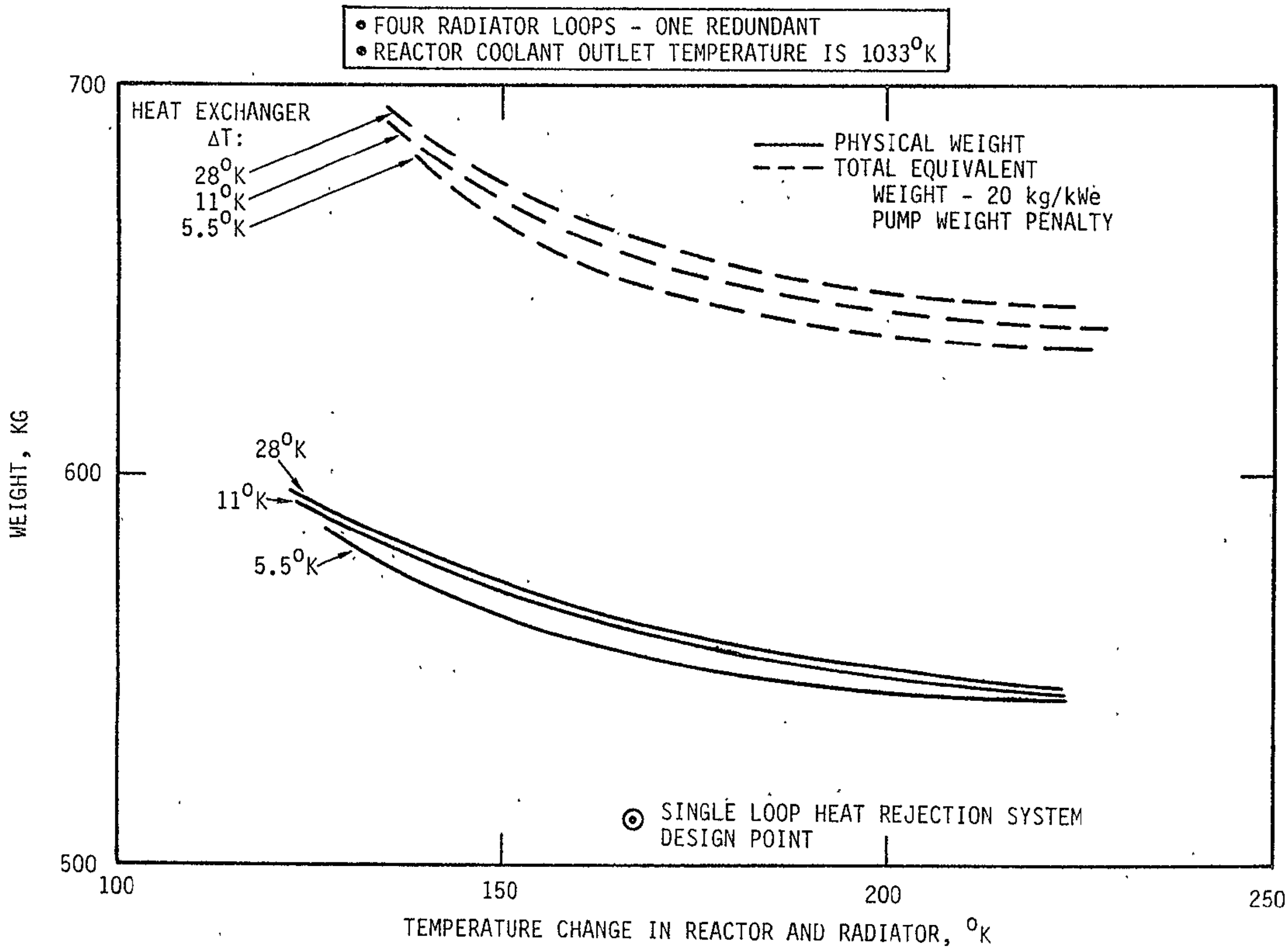
## TABLE 4-6

# EM PUMP COMPARISON
# HCD REACTOR SPACECRAFT

| PARAMETER | AC PUMP | DC PUMP |
| --- | --- | --- |
| PROPULSION SYSTEM SPECIFIC WEIGHT, kg/kWe | 27.7 | 28.3 |
| LAUNCH WEIGHT, kg | 8411 | 8553 |
| SPACECRAFT LENGTH, m | 21.9 | 23.5 |
| REACTOR OUTPUT POWER, kWe | 130.7 | 135.3 |
| POWER TO PUMP, kWe | 2.9 | 6.8 |
| PUMP WEIGHT, kg | 80 | 21 |
| HOTEL POWER CONDITIONER WEIGHT, kg | 14 | 20 |
| HOTEL POWER CONDITIONER EFFICIENCY, PERCENT | 90 | 60 |
| PUMP CABLE WEIGHT, kg | 2 | 82 |

FIGURE 4-3

ALTERNATE HEAT REJECTION SYSTEM
FOR HCD REACTOR SPACECRAFT



- Hotel power conditioning weight increases slightly as a result of increased pumping power required.

Comparison of the baseline design and the design based on multiple radiator loops is presented in Table 4-7. For this alternate HCD reactor spacecraft design, propulsion system specific weight increases 0.3 kg/kWe, and required reactor output increases to 131 kWe. To compensate for the heavier forward end of the spacecraft, the net payload is boomed 0.3 m from the spacecraft.

TABLE 4-7

COMPARISON OF BASELINE AND MULTIPLE RADIATOR LOOP CONFIGURATIONS OF HCD REACTOR SPACECRAFT

| PARAMETER | BASELINE DESIGN | | MULTIPLE RADIATOR LOOP DESIGN | |
|---|---|---|---|---|
| Spacecraft Length, m | | 21.9 | | 22.9 |
| Spacecraft Diameter, m | | 1.14 | | 1.14 |
| Spacecraft Weight, kg | | | | |
| Propulsion System | | 3322 | | 3359 |
| Power System | 2490 | | 2527 | |
| Thrust System | 832 | | 832 | |
| Propellant System | | 3770 | | 3770 |
| Net Spacecraft | | 662 | | 662 |
| Flight Shroud Penalty | | 657 | | 657 |
| Total Launch Weight | | 8411 | | 8449 |
| Propulsion System Specific Weight, kg/kWe | | 27.7 | | 28.0 |
| Electrical Power Distribution kWe | | | | |
| Reactor Power Output | | 130.7 | | 131 |
| Spacecraft Load | 114.98 | | 115.26 | |
| Electrical Losses | 15.72 | | 15.74 | |
| Payload Distribution | | | | |
| Percent in Forward Bay | 0 | | | 0 (Boomed |
| Percent at end of Spacecraft | 100 | | | 100 0.3m) |
| Heat Rejection Subsystem | | | | |
| Heat Exchanger T, °K | 167 | | | 139 |
| Main Radiator T, °K | 28 | | | 5.5 |

## 5.0 REFERENCES - VOLUME II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